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PAPER

Instabilities in magnetized inhomogeneous dusty plasmas with the effect of recombination

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Keywords: dusty plasma, recombination rate, inhomogeneous magnetized plasma

Abstract

An analytical formalism to understand the impact of various parameters on evolving instabilities in inhomogeneous collisional dusty plasmas is presented here under the effect of recombination. The basic fluid dynamics for electrons and singly charged cold ions is carried out including recombination and collision at constant rate at the surface of dust particles. Dust particles are considered to be static with unperturbed density. Normal mode analysis method has been used along with linear approximation to get perturbed densities (n_{i1}, n_{e1}) which are used along with quasi-neutrality condition to get perturbed potential (φ_1), using Poisson's equation to obtain dispersion relation. While other authors have detected instabilities in unmagnetized plasmas, here this method has been successfully realized in presence of static magnetic field at various propagation angle and allowed the straightforward calculation of growth rates of observed instability. An extensive study of the unstable modes has been done which are well discriminated and plotted with respect to different plasma parameters like dust charge, dust density, propagation angle, magnetic field, electrostatic potential along with plasma oscillation wavelength to Debye wavelength ratio. We have observed in the said model that the presence of dust particles and propagation angle of applied magnetic field are affecting significantly the growth rate of instability as compared to magnetic field and recombination.

1. Introduction

Two elements namely plasma and charged dust constitute the major part of universe [1]. Dusty plasma is combination of this charged dust, ions, electrons and neutral particles [2]. Change in intrinsic and extrinsic properties of dust particles introduces complexity in the plasma behavior; therefore dusty plasma is called 'complex plasma'. This complexity is in the form of influencing or governing some physical processes related to propagation of waves, instabilities, ionization and recombination on the surface of charged dust in plasma [1, 3, 4].These mutations cause inhomogeneous state and change in the well-known quasi-neutrality of plasma, analogous to the irregular distribution of charged dust particles [1].

Instability is always a motion which decreases the free energy and brings the plasma closer to the true thermodynamic equilibrium. Type of instability always depends on the free energy available to derive them. In two stream instability (TSI) electrons and ions having two different drift velocities flow in two different streams [5–7]. Numerous researchers tried and have been trying to elaborate the nature of two stream instability with the help of different techniques and methods. An important numerical analysis is done by Harris [5] using variational principle and WKB approximation with the result of instability corresponding to lower as well as higher mode oscillations. Effect of magnetic field with random obliqueness, on electromagnetic instability as compared to electrostatic instability has also been analyzed [6]. A study on instability in multispecies plasma demonstrated that the growth rate of instability was dependent on the population of species [7]. An analytical study was introduced by Uhm [8] about the change in behavior of instability due to a relative electron beam passing through a collisionless plasma also a sudden growth in beam current for instability was found due to electromagnetic effect. Rosenberg and Kral [9] observed modified TSI under the effect of magnetic field and proposed protostellar clouds and planetary rings as one of the applications of low frequency instability. Rosenberg and Shukla together introduced 'Laboratory Plasma Crystals' as the application of instability [10] and dust acoustic and TSI in collisional highly magnetized plasma [11].The growth rate of oscillating TSI (OTSI) in multispecies magnetized plasma, decreases first due to population of positrons in plasma and thereafter it increases due to pump electric field [12]. The behavior of growth rate of OTSI in plasma driven by relativistic electron beam has also been investigated and it was projected that the growth of interacting waves during the instability was seriously affected by the relative motion between the beam electrons and the background plasma particles [13].

Plasma parameters like temperature, density gradient and charge of dusty plasma species substantially affect phase velocity of dust acoustic waves in inhomogeneous dusty plasma [14]. The behavior of electrostatic drift waves of very low frequency, appearing as due to the motion of plasma particles across the static magnetic field and the inhomogeneity introduced by the distribution of the particles in the dusty plasma has been studied using the kinetic Vlasov model in plasmas [15]. An investigation on dust acoustic instabilities in colllisional unmagnetized plasma with the influence of background pressure of neutrals discovered both short and long wavelength mode instabilities driven by ion-dust relative drift and recombination of ion and electron [16–19]. Dust acoustic instabilities in unmagnetized dusty plasma with the effect of recombination and collision have also been studied and it was concluded that the recombination dominates in laboratory and fusion plasma and dust–neutral collision was more effective in space plasma [18]. Jyoti [20] have done an investigation on TSI in an inhomogeneous magnetized plasma with the impact of ionization and observed the growth of instabilities corresponding to long as well as short wavelength oscillations using various plasma parameters. Many researchers [21, 22] have confirmed the effect of recombination along with polarization force on gravitational instabilities. Multiscale cooperative micro excitations and structural rearrangements in cold dusty plasmas have been studied by Hau *et al* [23]. Besides, the experiments performed by Paz-Soldan *et al* [24] have confirmed the large-scale MHD instabilities by the injection of deuterium in JET tokamak. In another investigation [25], the effect of plasma absorption on lattice waves in 2D hexagonal dust crystals has been analyzed for which the dispersion relations with the effect of plasma absorption are derived. Similar efforts have been made by Bokaeeyan *et al* to study the propagation of dust lattice waves (DLWs) in a two-dimensional bi-crystal lattice in an arbitrary direction under zero gravity [26]. Also, the possibilities of instabilities in the cross-field plasmas including hall thrusters, magnetic nozzle have been reported [27–29] where the influence of electric potential and magnetic field is considered. The dust particles play an important role in plasma sheaths, optics, computational fluid study and lasers as well [30–34].

Based on aforementioned literature, here we present an extended model on magnetized inhomogeneous and collisional plasma with the effect of recombination at constant rate to elaborate more features in the detected instability. In the following sections, we have discussed the basic fluid equations, methodology along with results and discussion.

2. Fundamental fluid dynamics

To calculate and analyze TSI, present formulation assumes a dusty plasma model which is inhomogeneous, magnetized and collisional due to random distribution of charged dust, along with recombination, available at the surface of charged dust. Magnetic field (B_0) with constant strength is considered along z-direction at an angle (θ) with the electron stream. Dust is considered to be positively as well as negatively charged at the same time and static too with unperturbed density. Here, electrons are taken to be moving faster than ions with equal density. Temperature of plasma ions is considered to be zero and they are singly charged. The basic equations for magnetized inhomogeneous plasma with a significant recombination and collision rate can be written as-

$$\frac{\partial n_i}{\partial t} + \vec{\nabla} \cdot (n_i v_i) + V_0 \cdot \vec{\nabla} n_i + f_R n_{d0} = 0 \tag{1}$$

$$m_i n_i \left[\frac{\partial \vec{v}_i}{\partial t} + (\vec{v}_i \cdot \vec{\nabla}) v_i\right] + m_i n_i f_{in} v_i + e Z_i n_i \vec{\nabla} \varphi$$
$$- n_i Z_i e(\vec{v}_i \times \vec{B}_0) + \vec{\nabla} p_i = 0 \tag{2}$$

$$\frac{\partial n_e}{\partial t} + \vec{\nabla} \cdot (n_e \vec{v}_e) + V_0 \cdot \vec{\nabla} n_e + f_R n_{d0} = 0 \tag{3}$$

$$m_e n_e \left[\frac{\partial \vec{v}_e}{\partial t} + (\vec{v}_e \cdot \vec{\nabla}) v_e\right] + m_e n_e f_{en} v_e - e n_e \vec{\nabla} \varphi$$
$$- n_e e(\vec{v}_i \times \vec{B}_0) + \vec{\nabla} p_e = 0 \tag{4}$$

$$-\varepsilon_0 \nabla^2 \varphi = -en_e + eZ_i n_i + eZ_d n_{d0} \tag{5}$$

Here n_j stands for density of dusty plasma components ($j = e,\ i,\ d$) and n_d is considered to be unperturbed density (n_{d0}), m_j denotes mass of plasma components ($j = e,\ i,\ d$), v_j is fluid velocity of plasma components ($j = e,\ i,\ d$) and v_d is considered constant. V_0 is relative drift between ions and dust grains. $f_R = \beta\pi r_d^2 C_S$ is recombination frequency which is considered as constant. The pressure force is given by $p_e = C_e T_e n_e$ and $p_i = C_i T_i n_i$ where C_e and C_i are the specific heat ratio for the electrons and ions. Z_d and Z_i are charges on dust particles and ions respectively. The temperature of the electrons is represented by T_e, φ is the electrostatic potential and ε_0 is the permittivity of space. Here, f_{in} and f_{en} are ion-neutral and electron-neutral collision frequencies respectively, for momentum loss. Rest quantities have their usual meanings. Equations (1) and (3) are continuity equations for ions and electrons respectively. Equations (2) and (4) are equations of motion for ions and electrons respectively and equation (5) is Poisson's equation.

3. Methodology

To solve these equations normal mode analysis method is used. Physical quantities n_i, n_d, n_e, v_{ix}, v_{iy}, v_{iz}, v_{ex}, v_{iy}, v_{iz} and φ are expanded as $M = M_0 + M_1$, where M_0 stands for unperturbed part and M_1 stands for perturbed part of relative quantity.

Linearization is done by neglecting higher order perturbation terms including second order owing to their small magnitude. Considering a plane wave solution of the form $e^{i(kx-\omega t)}$ for the perturbed quantities and using $\frac{\partial}{\partial x} = iksin\theta$ and $\frac{\partial}{\partial x} = iksin\theta$, along with $\frac{\partial}{\partial t} = -i\omega$; the perturbed velocities for ions and electrons u_{i1} and u_{e1}, are obtained from momentum equations. These values are substituted in the expression for perturbed densities of electrons (n_{e1}) and ions (n_{i1}) obtained from continuity equations in order to have perturbed densities in terms of unperturbed parameters only. While doing this, we have assumed unperturbed densities of ions and electrons as constant with respect to electron oscillation period, so that

$$\frac{\partial n_{i0}}{\partial t} = \frac{\partial n_{e0}}{\partial t} = 0 \tag{6}$$

Also, we have used

$$\frac{\partial v_{ix0},\ v_{iy0},\ v_{iz0}}{\partial x,\ z} = 0 \tag{7}$$

$$\frac{\partial v_{ex0},\ v_{ey0}, v_{ez0}}{\partial t} = 0 \tag{8}$$

After using all these equations, we could find out the perturbed densities of ions and electrons as given below:

$$n_{i1} = \left[\frac{\begin{array}{c}[J_i G_i\{Cn_{d_0} - ik\sin\theta n_{i0}(v_{ix0} + V_0) - ik\cos\theta n_{i0}(v_{iz0} + V_0)\} - 2ik\sin\theta n_{i0}^2 \\ \{G_i^2(-A_i v_{ix0} + H_i v_{iy0}) - ik\sin\theta G_i^2 \delta_i - G_i n_{i0}(A_i H_i v_{iy0} + H_i^2 v_{ix0})\} \\ +2ik\cos\theta n_{i0}^2 J_i(ik\cos\theta\delta_i + A_i v_{iz0})]\end{array}}{\begin{array}{c}Q_i J_i G_i + 2ik\sin\theta n_{i0}\{G_i^2(-A_i v_{ix0} + H_i v_{iy0}) - G_i^2 ik\sin\theta(D_i + eZ_i\varphi_0) \\ -G_i n_{i0}(A_i H_i v_{iy0} + H_i^2 v_{ix0})\} - 2ik\cos\theta n_{i0} J_i\{ik\cos\theta(D_i + eZ_i\varphi_0) + A_i v_{iz0})\end{array}}\right] \tag{9}$$

Where

$$J_i = G_i^2 + H_i^2 n_{i0}^2$$

$$G_i = -i\omega + ik\sin\theta M_i(v_{ix0} + v_{iz0}) + A_i n_{i0}$$

$$Q_i = -i\omega + ik\sin\theta(v_{ix0} + V_0) + ik\cos\theta(v_{iz0} + V_0)$$

$$\delta_i = eZ_i(\varphi_0 + \varphi_1) + D_i$$

$$A_i = m_i f_{in}$$

and

$$H_i = eZ_i B_0$$

$$D_i = C_P T_P$$

and

$$M_i = m_i n_{i0}$$

$$n_{e1} = \left[\frac{\begin{array}{c} [J_e G_e\{Cn_{d_0} - ik\sin\theta\, n_{e0}(v_{ex0} + V_0) - ik\cos\theta n_{e0}(v_{ez0} + V_0)\} - 2ik\sin\theta n_{e0}^2 \\ \{G_e^2(-A_e v_{ex0} + H_e v_{ey0}) - ik\sin\theta G_e^2 \delta_e - G_e n_{e0}(A_e H_e v_{ey0} + H_e^2 v_{ex0})\} \\ +2ik\cos\theta n_{e0}^2 J_e(ik\cos\theta\delta_e - A_e v_{ez0})] \end{array}}{\begin{array}{c} Q_e J_e G_e + 2ik\sin\theta n_{e0}\{G_e^2(-A_e v_{ex0} + H_e v_{ey0}) + G_e^2 ik\sin\theta(-D_e + e\varphi_0) \\ -G_e n_{e0}(A_e H_e v_{ey0} + H_e^2 v_{ex0})\} + 2ik\cos\theta n_{e0} J_e\{ik\cos\theta(-D_e + e\varphi_0) - A_e v_{ez0}) \end{array}} \right] \tag{10}$$

Where

$$J_e = G_e^2 + H_e^2 n_{e0}^2$$
$$G_e = -i\omega + ik\sin\theta\, M_e(v_{ex0} + v_{ez0}) + A_e n_{e0}$$
$$Q_e = -i\omega + ik\sin\theta(v_{ex0} + V_0) + ik\cos\theta(v_{ez0} + V_0)$$
&
$$\delta_e = eZ_e(\varphi_0 + \varphi_1) - D_e$$
$$A_e = m_e f_{en}$$
&
$$H_e = eB_0$$
$$D_e = C_e T_e$$
&
$$M_e = m_e n_{e0}$$

Using these values of densities along with the quasi-neutrality condition in the Poisson's equation we get an equation for φ_1 in terms of unperturbed physical parameters as given below:

$$\varphi_1 = \frac{\varphi_N}{\varphi_D} = \frac{\varphi_{NR} + i\varphi_{NI}}{\varphi_{DR} + i\varphi_{DI}} \tag{11}$$

Where

$$\varphi_N = \varphi_{NR} + i\varphi_{NI}$$
$$\varphi_N = \varphi_{NR} + i\varphi_{NI} = S_N R_D + R_N S_D$$

Where

$$\begin{aligned} S_N = {} & -J_e G_e eCn_{d0} \\ & -A_e v_{ex0} i2k\sin\theta e n_{eo}^2 G_e^2 \\ & +i2k\sin\theta e n_{eo}^2 G_e^2 eB_0 v_{ey0} \\ & -2k\sin\theta e n_{eo}^2 G_e^2 k e n_{e0} J_e G_e \sin\theta(v_{ex0} + V_0) \\ & -2k\sin\theta e n_{eo}^2 G_e^2 k e n_{e0} J_e G_e \cos\theta(v_{ez0} + V_o) \\ & -2k\sin\theta e n_{eo}^2 G_e^2 k\sin\theta(-D_e + e\varphi_0) \\ & -i2k\sin\theta e n_{eo}^2 eB_0 n_{e0} G_e(A_e v_{ey0} + eB_0 v_{ex0}) \\ & +2ik\cos\theta e n_{e0}^2 J_e\{-A_e v_{ez0} + ik\cos\theta(-D_e + e\varphi_0)\} \end{aligned}$$

$$\begin{aligned} R_N = {} & -eZ_i Cn_{d0} J_i G_i \\ & -ikeZ_i n_{e0} J_i G_i \cos\theta(v_{iz0} + V_o) \\ & -ikeZ_i n_{e0} J_i G_i \sin\theta(v_{ix0} + V_0) \\ & +i2k\sin\theta eZ_i n_{io}^2 \\ & [G_i^2\{A_i v_{ix0} - eZ_i B_0 v_{iy0} + ik\sin\theta(D_i + eZ_i\varphi_0)\} \\ & +eZ_i B_0 n_{i0} G_i(A_i v_{iy0} + eZ_i B_0 v_{ix0})] \\ & +2ik\cos\theta eZ_i n_{i0}^2 J_i\{A_i v_{iz0} + ik\cos\theta(D_i + eZ_i\varphi_0)\} \end{aligned}$$

And

$$\varphi_D = \varphi_{DR} + i\varphi_{DI}$$
$$\begin{aligned} \varphi_D = \varphi_{DR} + i\varphi_{DI} = {} & [\varepsilon_0 k^2 S_D R_D + 2k^2 e^2 n_{e0}^2(\sin^2\theta G_e^2 + \cos^2\theta J_e) \\ & R_D + 2k^2 e^2 Z_i^2 n_{i0}^2(\sin^2\theta G_i^2 + \cos^2\theta J_i) S_D] \end{aligned}$$

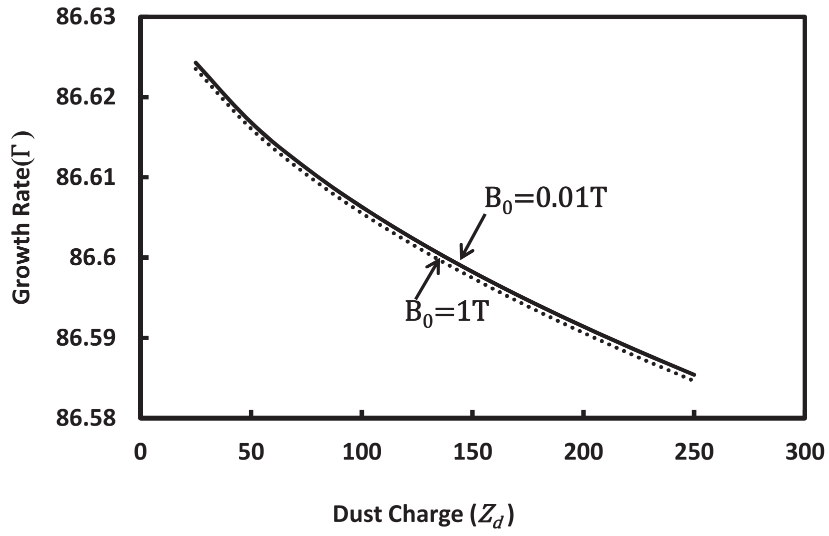

Figure 1. Variation of normalized growth rate Γ with dust charge Z_d for two different values of $B_0 = 0.1$T and 1T, when $\varphi_0 = 0.5$V, $n_{e0} = n_{i0} = 5 \times 10^{17} m^{-3}$, $v_{ix0} = v_{iy0} = v_{iz0} = 0.3\ C_s$, $v_{ex0} = v_{ey0} = v_{ez0} = 6\ C_s$, $T_e = 0.3\ eV$, $T_p = 0$, $Z_i = 1$, $Z_d = 200$, $C_s = 1.7 \times 10^4$ m sec^{-1}, $f_R = 5.32 \times 10^{-10}$ s^{-1}, $\frac{\lambda}{\lambda_{De}} = 5$.

Where

$$S_D = Q_e J_e G_e + 2ik \sin\theta n_{e0}[G_e^2\{-A_e v_{ex0} + eB_0 v_{ey0} + ik \sin\theta(-D_e + e\varphi_0)\} - eB_0 n_{e0} G_e(A_e v_{ey0} + eB_0 v_{ex0})] + 2ik \cos\theta n_{e0} J_e\{-A_e v_{ez0} + ik \cos\theta(-D_e + e\varphi_0)\}$$

$$R_D = Q_i J_i G_i + 2ik \sin\theta n_{i0}[G_i^2\{-A_i v_{ix0} + eZ_i B_0 v_{iy0} - ik \sin\theta(-D_i + eZ_i\varphi_0)\} - eZ_i B_0 n_{i0} G_i(A_i v_{ix0} + eZ_i B_0 v_{ix0})] - 2ik \cos\theta n_{i0} J_i\{A_i v_{iz0} + ik \cos\theta(D_i + eZ_i\varphi_0)\}$$

In equation (11) φ_1 is expressed in terms of unperturbed quantities. Since a perturbed quantity cannot be expressed as explicit function of unperturbed quantities only, so we considered R.H.S. as undetermined by putting both numerator and denominator individually as zero. Thus, we get four polynomial equations, of order seven and eight, as dispersion relations. These dispersion relations are solved for values of ω using typical plasma parameters. It has been found that some of the roots are real (corresponding to propagating modes which are not part of this article) and rest are complex whose imaginary parts correspond to propagating waves. The complex roots always occur in conjugate pairs; one of them (with positive imaginary part) gives propagating wave and the other (with negative imaginary part) gives damped wave.

4. Results and discussion

The plasma model we have considered here supports several instabilities but most of them disappear frequently except the one. Normalized growth rates $\left(\Gamma = \frac{\omega_{Im}}{\omega_{pe}}\right)$ of the existing instability has been governed for variation with magnetic field (B_0), potential (φ_0), dust charge (Z_d)and unperturbed dust density (n_{do}), direction of propagation (θ), and recombination frequency (f_R) with propagation vector along with Plasma Oscillation wavelength to Debye Wavelength ratio. Here, it is pertinent to mentioned that the combined effect of dust particles and recombination has been investigated by other researchers as well [17, 19] but they had not observed the effects in the presence of magnetic field, considering fluid like stream of negatively charged electrons instead of Boltzmann's distribution of electrons.

From figure 1, we can see that the growth rate of instability is gradually decreasing with increase in the charge of dust particles. Interestingly, at lower values (in the range of 0.01T to 0.09T) as well as higher values (0.1T to 1T) of magnetic field the growth rate is decreasing at the same rate, possessing almost same magnitude unlike that observed in earlier report [20] where instabilities grew significantly with increase in magnetic field without considering the effect of recombination and in absence of dust particles. In another study, carried out similarly, the damping of growth rate was observed for variation in charged dust in absence of magnetic field [18] while

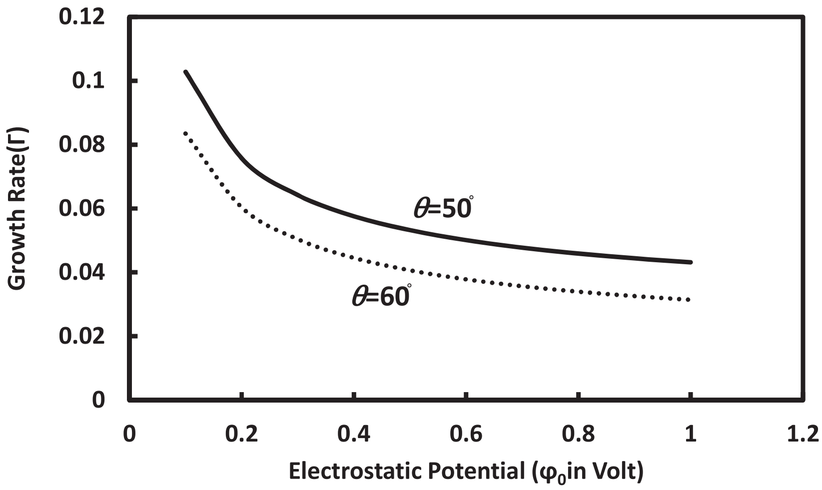

Figure 2. Variation of normalized growth rate Γ of single instability with electrostatic potential (φ_0)for two different values of propagation angle $\theta = 50°$ and $60°$ when $B_0 = 0.5\text{T}$, $n_{e0} = n_{i0} = 5 \times 10^{17} m^{-3}$, $v_{ix0} = v_{iy0} = v_{iz0} = 0.3\ C_s$, $v_{ex0} = v_{ey0} = v_{ez0} = 6\ C_s$, $T_e = 0.3eV$, $T_p = 0$, $Z_i = 1$, $Z_d = 200$, $C_s = 1.7 \times 10^4$ m sec^{-1}, $f_R = 5.32 \times 10^{-10}$ s^{-1}, $\frac{\lambda}{\lambda_{De}} = 5$.

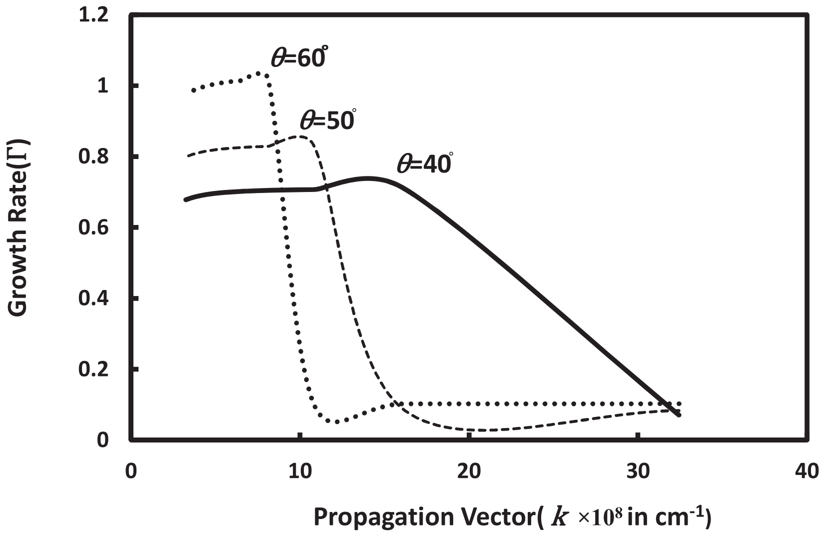

Figure 3. Variation of normalized growth rate Γ of single instability with propagation vector(k) for three different values of propagation angle $\theta = 40°$, $50°$ and ,when $\varphi_0 = 0.1\text{V}$, $B_0 = 0.5\text{T}$, $n_{e0} = n_{i0} = 5 \times 10^{17} m^{-3}$, $v_{ix0} = v_{iy0} = v_{iz0} = 0.3\ C_s$, $v_{ex0} = v_{ey0} = v_{ez0} = 6\ C_s$, $T_e = 0.3eV$, $T_p = 0$, $Z_i = 1$, $Z_d = 200$, $C_s = 1.7 \times 10^4$ m sec^{-1}, $f_R = 5.32 \times 10^{-10}$ s^{-1}, $\frac{\lambda}{\lambda_{De}} = 10$.

increase in growth rate with charged dust is reported in Hall thrusters [28]. Hence, it is logical to conclude that this instability is driven by recombination effect with lighter impact of magnetic field.

Extensive simulations have been done by Bret *et al* [35] and by Alcusón *et al* [36] for observing the effects of electrostatic potential. However, analytical studies in this direction are rare. Here, in this article, in figures 2 and 3, we notice the combined effect of electrostatic potential and the obliqueness (propagation angle) of magnetic field which is quite significant as we know that the charge particles do feel the effect of Lorentz force when both the fields are present. In figure 2, we can see that the instability is reducing its growth rate with increase in electrostatic potential although this decrement at higher values of potential is very low and growth rate is of lower magnitude at higher value of propagation angle.

But in figure 3, this effect has been reversed. At lower values of propagation vector (k), we have higher growth rate magnitude for higher value of propagation angle which is an interesting result as such observations are hitherto unreported in the literature. We observe similar kind of behaviour for all values of propagation angle in which instability has higher magnitude for lower values of k and it decreases sharply before attaining saturated values of growth rate for a considerable range of k values, under the effect of recombination [17–19].

From figure 4, we observe that the recombination does not affect the growth rate of this instability although the magnitude is being affected by propagation angle significantly. This result is in agreement with Mamun and

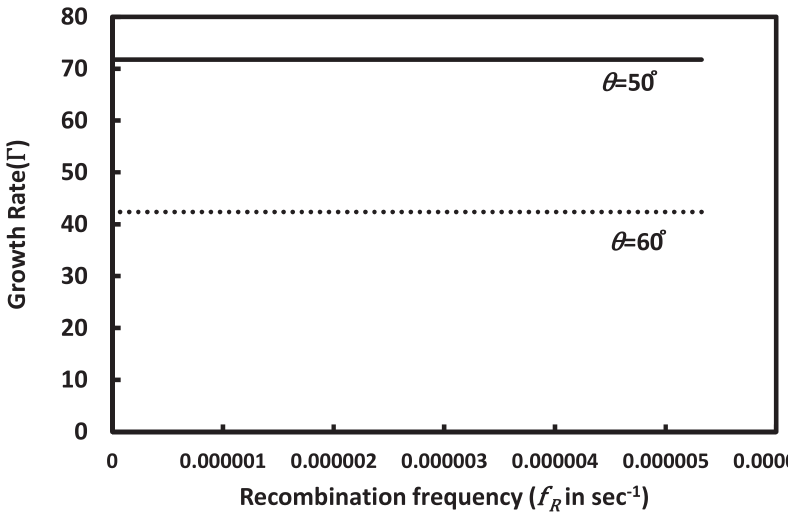

Figure 4. Variation of normalized growth rate Γ of single instability withrecombination frequency (f_R) for two different values of propagation angle $\theta = 50°$ and 60°, when $\varphi_0 = 0.5$V, $B_0 = 0.1$T, $n_{e0} = n_{i0} = 5 \times 10^{17} m^{-3}$, $v_{ix0} = v_{iy0} = v_{iz0} = 0.3\ C_s$, $v_{ex0} = v_{ey0} = v_{ez0} = 6\ C_s$, $T_e = 0.3eV$, $T_p = 0$, $Z_i = 1$, $Z_d = 100$, $C_S = 1.7 \times 10^4$ m sec^{-1}, $\frac{\lambda}{\lambda_{De}} = 5$.

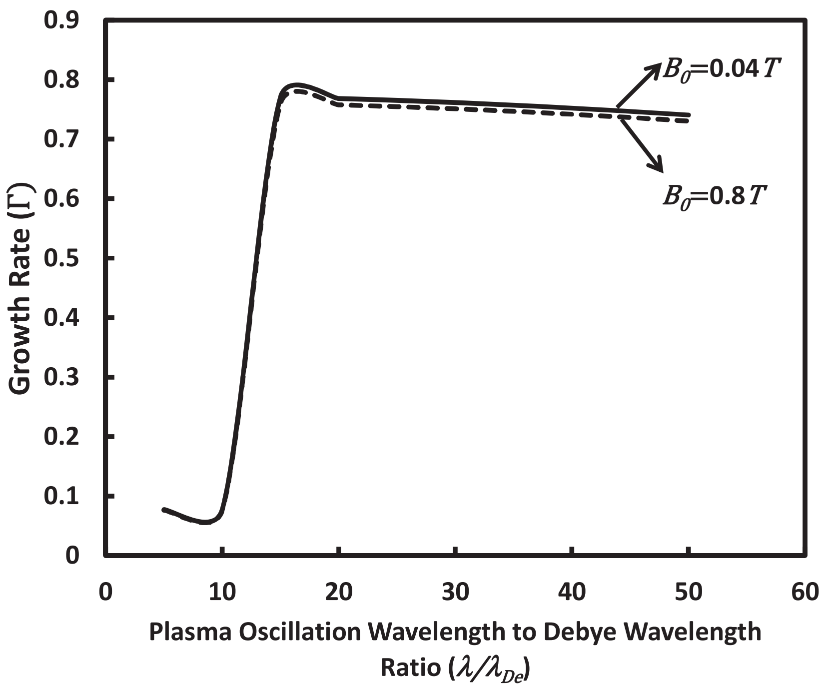

Figure 5. Variation of normalized growth rate Γ of single instability with plasma oscillation wavelength to Debye wavelength ratio (λ/λ_{De}) for two different values of magnetic field $B_0 = 0.04$T and 0.8T when $\varphi_0 = 0.1$V, $\theta = 45°$, $n_{e0} = n_{i0} = 5 \times 10^{17} m^{-3}$, $f_R = 5.32 \times 10^{-10}$ s^{-1}., $v_{ix0} = v_{iy0} = v_{iz0} = 0.3\ C_s$, $v_{ex0} = v_{ey0} = v_{ez0} = 6\ C_s$, $C_S = 1.7 \times 104$ m sec^{-1}. $T_e = 0.3eV$, $T_p = 0$, $Z_i = 1$, $Z_d = 100$.

Shukla [19] where they have reported negligible effect of recombination. Similar kind of effect has been observed by Bose and Bal [18] in short wavelength regime with a contrast in long wavelength regime where recombination was a dominating factor. This is because of the fact that the dust-neutral collisions have been neglected here and the constant rate of recombination in presence of stationary dust particles is taken into account [18]. As we know that the recombination frequency is dominant over dust-neutral collision frequency in laboratory plasma as well as in fusion plasma whereas the dust-neutral collision frequency is dominant in the interstellar plasmas, we can conclude through these results that on the application of magnetic field also for lower values of plasma oscillation to Debye wavelength ratio, the recombination is not the dominating factor to decide the growth rate of magnetic field.

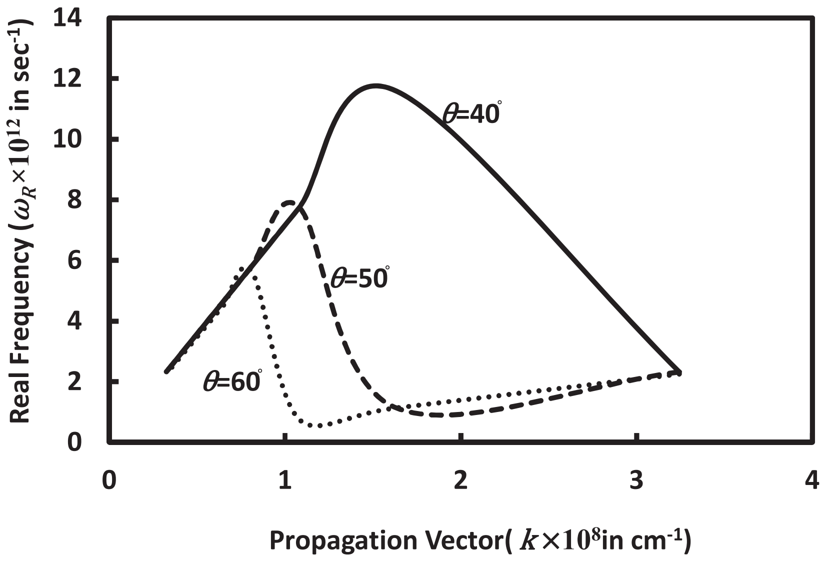

Figure 6. Variation of real frequency ω_R of single instability with propagation vector(k) for three different values of propagation angle $\theta = 40°$, $50°$ and $60°$ when $\varphi_0 = 0.1$V, $B_0 = 0.5$T, $n_{e0} = n_{i0} = 5 \times 10^{17} m^{-3}$, $v_{ix0} = v_{iy0} = v_{iz0} = 0.3\ C_s$, $v_{ex0} = v_{ey0} = v_{ez0} = 6\ C_s$, $T_e = 0.3eV$, $T_p = 0$, $Z_i = 1$, $Z_d = 200$, $C_S = 1.7 \times 10^4$ m s^{-1}., $f_R = 5.32 \times 10^{-10}$ s^{-1}, $\frac{\lambda}{\lambda_{De}} = 10$.

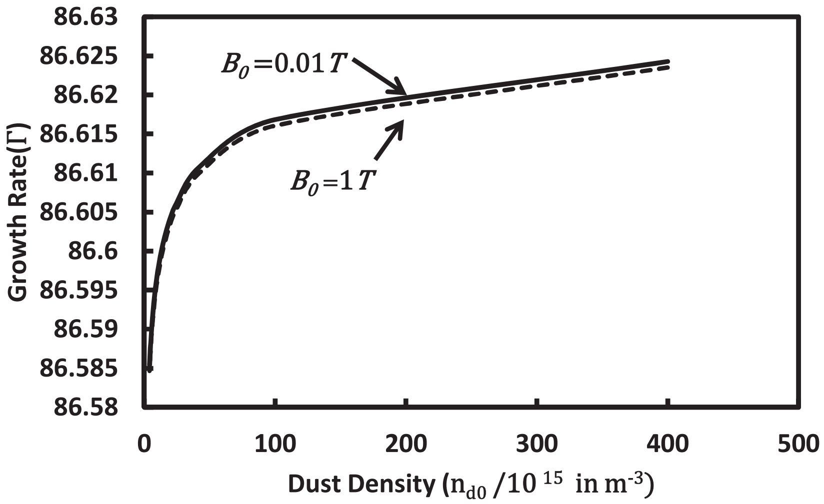

Figure 7. Variation of normalized growth rate Γ of instability with dust density n_{do} when $\varphi_0 = 0.5$V, $\theta = 45°$, $n_{e0} = n_{i0} = 5 \times 10^{17}$ m^{-3}, $f_R = 5.32 \times 10^{-10}$ s^{-1}, $v_{ix0} = v_{iy0} = v_{iz0} = 0.3\ C_s$, $v_{ex0} = v_{ey0} = v_{ez0} = 6\ C_s$, $C_S = 1.7 \times 10^4$ m s^{-1} $T_e = 0.3\ eV$, $T_p = 0$, $Z_i = 1$ and $\frac{\lambda}{\lambda_{De}} = 5$.

From figure 5, it can be inferred that the instability is significantly affected by plasma oscillation wavelength to Debye wavelength ratio (λ/λ_{De}) irrespective of the magnitude of externally applied magnetic field. We notice the presence of magnetic field along with recombination factor and absence of the dust neutral collisions in dusty plasmas does not influence the instability unlike earlier work [20] where magnetic field is having a significant effect in presence of ionization constant in non-dusty plasmas. Here, we can also conclude that the instability carries higher growth rate at larger values of plasma oscillation to Debye wavelength ratio unlike the case of Chaudhary *et al* [20] where two instabilities were observed and both carry the higher magnitude of growth rate at lower values of plasma to Debye wavelength ratio in presence of constant rate of ionization.

Figure 6 shows that with increase in the values of propagation vector, the real frequency first increases linearly and then drops again after attaining a peak unlike the results of Bal *et al* [18] where no such dips were observed even though the initial behavior was same. This implies that the phase velocity initially remains constant but later its magnitude is decided by the propagation angle as we can see the slope of the curves at higher values of propagation vector is sharper. The dip can be observed clearly at higher values of propagation angle before attaining a constant value of real frequency which means the phase velocity will decrease with increase in

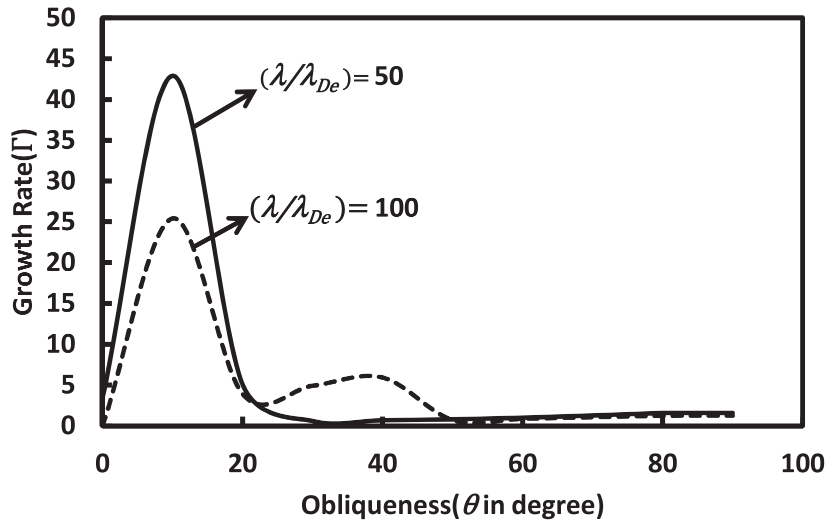

Figure 8. Variation of normalized growth rate Γ of single instability with obliqueness (θ) for two different values of plasma oscillation wavelength to Debye wavelength ratio $\lambda/\lambda_{De} = 50$ and 100 when $B_0 = 0.5T$, $\varphi_0 = 0.1\text{V}$, $n_{e0} = n_{i0} = 5 \times 10^{17} m^{-3}$, $f_R = 5.32 \times 10^{-10}$/sec., $v_{ix0} = v_{iy0} = v_{iz0} = 0.3\, C_s$, $v_{ex0} = v_{ey0} = v_{ez0} = 6\, C_s$, $C_S = 1.7 \times 10^4$ m sec^{-1}. $T_e = 0.3\, eV$, $T_p = 0$, $Z_i = 1$, $Z_d = 100$, $\frac{\lambda}{\lambda_{De}} = 5$.

propagation vector with higher values unlike the case of Chaudhary *et al* [20] where phase velocity attained saturated and constant values.

Effect of dust density is observed in figure 7. Here we can see that with increase in dust density, the growth rate is increasing significantly. We can see that for smaller values of dust density the increase in growth rate is sharp while at higher dust density values the growth rate is high but rate of increase of it is smaller comparatively. Tyagi *et al* [28] have observed the opposite behavior in case of Hall Thrusters for magnetic field and dust density where dust impurities were under the effect of cross electric and magnetic field.

Combined effect of obliqueness of applied magnetic field along with Plasma oscillation wavelength to Debye wavelength ratio $\lambda/\lambda_{\text{De}}$ is shown in figure 8. We observe, irrespective of the $\lambda/\lambda_{\text{De}}$ values, the instability always peaks at smaller angle of obliqueness i.e., 10^0, however a negligible growth rate for higher values of θ in noticed. The growth rate is observed to be affected significantly for different values of $\lambda/\lambda_{\text{De}}$. Similar behavior has been reported by Chaudhary *et al* [20] where at lower values of $\lambda/\lambda_{\text{De}}$ growth rates were higher, along with smaller growth rate at higher values of θ in presence of constant ionization rate and in absence of dust particles.

5. Conclusion

Instability in the plasma in the presence of stationary dust particles under the effect of recombination has been observed. The effect of charged dust, its density, propagation angle, magnetic field, along with electrostatic potential has been studied for various plasma oscillation wavelength to Debye wavelength ratios. Since charged dust and its density plays a prominent role in affecting the growth rate, we can conclude that the observed instability is actually dust driven. The effect of propagation angle is found to be reversed at real frequencies for lower values of plasma to Debye wavelength ratio, while unaffected by recombination. However, for higher values of plasma to Debye wavelength ratio, the smaller propagation angles are significant. Instability is feebly affected by Magnetic field. In the said plasma model, dust neutral collisions have been ignored which are the dominating factor in interstellar plasmas. So, the same plasma model can further be explored after including dynamics of dust particles along with dust-neutral collisions which will act as source for sinking particles due to recombination.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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