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KINETIC BUNEMAN INSTABILITY IN DUSTY PLASMA OF DIFFERENT TEMPERATURE REGIMES

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Recent theoretical work on the excitation of Buneman's instability in inhomogeneous anisotropic dusty plasmas is presented. Plasmas with different temperature regime are considered. The dispersion relation is derived and solved for a 1-D Buneman instability excited in such plasmas. Electron to ion temperature ratio, degree of plasma inhomogeneity and dust grains thermal velocity are found to play a crucial role in the growth and damping of Buneman instability.

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1. *Introduction*

The Buneman instability [1 − 7] is one of the current-driven plasma instabilities. The Buneman instability represents the stimulated Cherenkov radiation of the low-frequency. The Buneman (electron-ion two streams) instability takes place in a current-driven system where electron and ion beams drift at different velocities. Strong electron streaming leads to the growing of Buneman instability. This growing mode leads to strong localized electric fields. The resulting electron scattering produces strong enhanced resistivity and electron heating [8].

From the experimental point of view, a rapidly growing of the ultra-high-frequency (UHF) (> 250 MHz) wave burst, identified as the Buneman two-stream instability, was detected at the beginning of a high-current plasma discharge [9]. The Buneman instability operates in both magnetized and unmagnetized plasmas near the electron plasma frequency (in the electron reference frame) and is excited when the electron drift velocity exceeds the electron thermal velocity [10 – 12].

Using strong electric fields in devices (experiments) for plasma turbulent heating, for plasma heating in discharges and closed magnetic traps, acceleration of plasmoids, or for inducing electric fields in plasmas, causes currents $\vec{u} = \vec{u}_e - \vec{u}_{i,d}$ due to the relative motion of electrons and ions (or dust). If u is comparable to the electron thermal velocity V_{Te} ($V_{Te} = \sqrt{T_e/m_e}$), the current Buneman's instability arises.

This type of instability is excited kinetically [13, 14], however, it is excited hydrodynamically when $\vec{u}$ considerably exceeds a certain threshold value ($u > u_{cr} \approx V_{Te}$). In this case, the development of the instability involves a displacement of the plasma regions and results in the variation of the spatial configuration of the plasma. On the other hand, near the threshold when $\Delta u = u - u_{cr}$, or when waves receive energy - due to Cherenkov resonance - from a small group of resonance particles, this instability becomes kinetic. In this case, the phase velocities of the waves are less by an order of magnitude than the thermal velocities of the particles.

As application, excluding the sheath regions, experiments in the magnetoplasmadynamic MPD thruster have shown that the electron drift velocity is only a small fraction of the electron thermal velocity, effectively stabilizing the Buneman instability. Streaming between reflected protons and upstream electrons gives rise to a strong Buneman instability [15, 16]. It is likely to attribute the Buneman instability and the modified twostream instability to play important roles in the production of high energy electrons at SNRs (supernova remnants). In astrophysical plasmas, the magnetic-reconnection Buneman instability may be excited [17].

Generally speaking, waves and instabilities occupy a significant part of modern plasma physics research because most properties of plasmas are related to the fundamental wave modes in laboratory and space plasma systems. In recent years, numerous studies have been confined to dusty plasmas having electrons, ions, and charged dust grains of spherical shapes [18 – 23].

When dust grains are immersed in plasma, they become negatively charged because impinging electrons move faster than impinging ions. The negatively-charged dust grains can be considered a third plasma species, so the plasma consists of electrons (negative), ions (positive), and dust grains (negative) [24].

In the presence of particle streaming, Jeans instability and the Buneman instability can overlap [25]. Further studies examined the influence of dust size distribution on the Jeans-Buneman instability [26]. Besides, the Buneman-type streaming instability may be developed in a low-temperature collisionless plasma in the presence of highly-charged impurities or dust and an ion flow. The important feature of the instability is that it takes place for supersonic as well as for subsonic velocities of the flow, thus being able to develop even in the pre-sheath and plasma bulk regions of low-temperature discharges where ion speeds are below the sound velocity [27].

Since charged dust in laboratory plasmas are generally levitated by electric fields, ions which acquire drifts due to these fields can stream through the dust, leading to various kinds of streaming instabilities, among them the Buneman instability. Recently, an ion-dust streaming instability with frequency less than the dust-neutral collision frequency was investigated [28]. The instability may have application to observations of waves in certain laboratory dc glow discharge dusty plasmas. Besides, dusty plasmas in the laboratory generally have finite spatial extent, therefore boundary effects may alter the properties of such ion-dust streaming instabilities. Recently, ion-dust streaming instability in plasma containing dust grains with large thermal speeds was considered using kinetic theory [29].

Buneman-type instabilities in a dusty plasma have been investigated before by many authors, e.g., ion-dust streaming instability in processing plasmas including collision effects [30], Buneman-type streaming instability in a plasma with dust particulates without collisions [27], and ion-dust two-stream instability in a collision including a magnetic field and collisions [31].

We extend previous work [13, 14, 32 – 36] by:

(i) including dust,

(ii) considering different temperature regimes, as mechanism for growing or damping of instability,

(iii) effects of plasma inhomegeneity (specially for weak or strong ion inhomogeneity) and dusts on the growing or damping of Buneman instability.

2. Kinetic dispersion relation

Let us consider an inhomogeneous plasma immersed in a static magnetic field $\vec{H}_0 = \vec{e}_z H_0$ with cold weakly magnetized dusts. Plasma density inhomogeneity is perpendicular to $\vec{H}_0$, i.e., directed along the z-axis.

In a dusty plasma, the quasi-neutrality condition should be adopted to include dust grains as

$$\sum_{\alpha}^{e,i,d} e_\alpha n_{\alpha\, 0} = 0\,.$$

For low β (the ratio of thermal to magnetic pressure), the kinetic dispersion relation governing the system is

$$\varepsilon(\vec{k},\omega) = 1 + \sum_{\alpha}^{e,i,d} \chi_\alpha = 0\,, \tag{1}$$

$$\chi_\alpha = \frac{\omega_{p\alpha}^2}{k_\parallel^2 V_{T\alpha}^2}\left[1 + \mathrm{i}\sqrt{\pi}\,\hat{l}_\alpha Z_\alpha W(Z_\alpha) A(\mu_\alpha)\right].$$

$k_\parallel$ is the wave number parallel to $\vec{H}_0$, χ_α are the plasma susceptibilities, α is the type of particles, i.e., $\alpha = e$, i, d, for electrons, ions and dusts, respectively. The operator $\hat{l}_\alpha$ represents the effect of plasma inhomogeneity in density and temperature,

$$\hat{l}_\alpha = 1 - \frac{k_\| V_{T\alpha}^2}{(\omega - \vec{k}\cdot\vec{u}_\alpha)\,\omega_{c\alpha}} \left[\frac{\partial}{\partial x}\ln n_\alpha + \frac{\partial}{\partial x}\ln T_\alpha\right],$$

and we are going to consider here only the density inhomogeneity, i.e., $\partial \ln T_\alpha/\partial x = 0$. $A(\mu_\alpha)$ represents the magnetic field effect, $A(\mu_\alpha) = I_0(\mu_\alpha)\mathrm{e}^{-\mu_\alpha}$, $\mu_\alpha = k_\perp^2 \rho_\alpha^2$, $k_\perp$ the wave number perpendicular to $\vec{H}_0$, $\rho_\alpha = V_{T\alpha}/\omega_{c\alpha}$ is the Larmor radius, $\omega_{c\alpha} = e_\alpha H_0/(m_\alpha c)$ is the cyclotron frequency, $V_{T\alpha} = \sqrt{T_\alpha/m_\alpha}$ the thermal velocity, $I_0(\mu_\alpha)$ is the modified Bessel function of the 0^{th} order, and $\omega_{p\alpha} = \sqrt{4\pi e^2 n_\alpha(x)/m_\alpha}$ is the Langmuir frequency. $W(Z_\alpha)$ is the probability integral with amplitude

$$Z_\alpha = \frac{\omega - \vec{k}\cdot\vec{u}_\alpha}{\sqrt{2}\;k_\| V_{T\alpha}}.$$

If $\vec{k}\cdot\vec{u}_i \approx \vec{k}\cdot\vec{u}_d$ ($\vec{u}_i \approx \vec{u}_d$), and we set $\omega' = \omega - \vec{k}\cdot\vec{u}_d = \omega - \vec{k}\cdot\vec{u}_i$, then Z_α for different species are

$$Z_e = \frac{\omega' - \vec{k}\cdot\vec{u}}{\sqrt{2}\;k_\| V_{Te}} \quad \text{and} \quad Z_{(i,d)} \cong \frac{\omega'}{\sqrt{2}\;k_\| V_{T(i,d)}},$$

where, $\vec{k}\cdot\vec{u} = ku\cos\theta$, and θ is the angle between $\vec{k}$ and $\vec{u} = \vec{u}_e - \vec{u}_i$. We consider dusty plasma consisting of fairly massive grains, i.e., $m_d/m_i \gg 1$.

3. *Thresholds*

For the excitation of instability we set $u \to u_{cr} + \Delta u$ $\omega' \to \omega_0 + \Delta\omega$, $\Delta\omega = \omega_k + \mathrm{i}\gamma_k$, where ω_k and γ_k are the frequency and growth rate of the instability, respectively, and u_{cr} and ω_0 are the threshold values of current velocity and frequency. Also, we set $Z_\alpha = Z_{\alpha 0} + \Delta Z_\alpha$. For such perturbations, we have $(\Delta u/u_{cr},\, \Delta\omega/\omega,\, \Delta k/k,\, \theta) \ll 1$.

Now, for weakly magnetized dusts, $\mu_d \ll 1$, and under the frequency ranges $|\vec{k}\cdot\vec{u}_i,\, \vec{k}\cdot\vec{u}_d| \ll \omega'$, $|\omega_{ne}| \ll |\omega' - \vec{k}\cdot\vec{u}|$ and $|\vec{k}\cdot\vec{u}| < \omega'$, the following relations are valid:

$$Z_{0i} \approx Z_{0d} \gg Z_{0e}, \quad Z_{0d} > 1, \quad Z_{0e} \ll 1, \quad Z_{0e} = \frac{\omega_0 - k u_{cr}}{\sqrt{2}\,k_\| V_{Te}}, \quad Z_{0(i,d)} = \frac{\omega_0}{\sqrt{2}\,k_\| V_{i,d}},$$

$$A(\mu_i) = \frac{1}{\sqrt{2\pi\mu_i}}, \quad A(\mu_e) = 1 - \mu_e, \quad A(\mu_d) = 1, \quad \hat{l}_{e,d} \approx 1, \quad \hat{l}_i \approx 1 - \frac{\omega_{ni}}{\omega_e},$$

where

$$\omega_{n\alpha} = \frac{k_\parallel V_{T\alpha}^2}{\omega_{c\alpha}}\chi_{n\alpha}, \quad \chi_{n\alpha} = \frac{\partial \ln n_{0\alpha}}{\partial x} .$$

Under the conditions

$$\frac{\omega_{ne}}{\omega_{ni}} = \left(\frac{T_e}{T_i}\right)\left(\frac{n_{0i}}{n_{0e}}\right)\left(\frac{\partial n_{0e}/\partial x}{\partial n_{0i}/\partial x}\right) \ll 1 ,$$

it is only the ions that have a density gradient and associated diamagnetic drift. Regardless the temperature ratio T_d/T_i, for a dusty plasma, we have

$$\frac{\rho_d}{\rho_i} = \sqrt{\frac{T_d}{T_i}}\sqrt{\frac{m_d}{m_i}} \gg 1 .$$

Accordingly, under the specific conditions mentioned above (which agrees with experiment), the dispersion relation (1) reads

$$1 + k^2 r_{de}^2 + \mathrm{i}\sqrt{\pi}(1-\mu_e)Z_e W(Z_e) + \frac{T_e}{T_i}\mathrm{i}\sqrt{\pi}\frac{1}{\sqrt{2\pi\mu_i}}\left(1 - \frac{\omega_{ni}}{\omega_0}\right)Z_i W(Z_i)$$

$$+\frac{T_e}{T_d}\frac{n_d}{n_e}\big(1 + \mathrm{i}\sqrt{\pi}\, Z_d W(Z_d)\big) = 0 \tag{2}$$

where, $r_{de} = V_{Te}/\omega_{pe}$ is the electron Debye radius.

According to the model and conditions described above, the dust is introduced in the dispersion relation (1), hence (2) is valid (see also Refs. [18, 19, 29, 32]).

Setting ω' into (2), assuming $\omega' \to \omega_0$ and $u \to u_{cr}$, we obtain the threshold velocity of instability as

$$u_{cr} = \sqrt{\frac{\pi}{8}}\frac{V_{Ti}}{\omega_{ci}}\left(1 - \frac{\omega_{ni}}{\omega_0}\right)^{-1}\frac{V_{Ti}}{V_{Te}}\frac{T_i}{T_e}\,\omega_0\left[1 + \frac{T_e}{T_d}\frac{n_d}{n_e}\frac{V_{Te}}{V_{Td}}\right]^2 . \tag{3}$$

For rarefied dust, $n_d/n_e \ll 1$, and with fulfillment of the condition $\frac{T_e}{T_d}\frac{n_d}{n_e}\frac{V_{Te}}{V_{Td}} \ll 1$, Eq. (3) reads

$$u_{cr} = \sqrt{\frac{\pi}{8}}\,\frac{V_{Ti}}{\omega_{ci}}\left(1 - \frac{\omega_{ni}}{\omega_0}\right)^{-1}\frac{V_{Ti}}{V_{Te}}\frac{T_i}{T_e}\,\omega_0 , \tag{4}$$

which shows that u_{cr} is completely independent of dust. On the other hand, for a strongly dusty plasma and fulfillment of the condition $\frac{T_e}{T_d}\frac{n_d}{n_e}\frac{V_{Te}}{V_{Td}} \gg 1$, u_{cr} reads

$$u_{cr} \cong \sqrt{\frac{\pi}{8}}\,\frac{V_{Te}}{\omega_{ci}}\left(\frac{V_{Ti}}{V_{Td}}\right)^2\frac{T_i}{T_e}\,\omega_0\left(\frac{T_e}{T_d}\right)^2\left(\frac{n_d}{n_e}\right)^2\left(1 + \frac{\omega_{ni}}{\omega_0}\right) , \tag{5}$$

Here, we have two cases concerning the degree of ion inhomogeneity, i.e., strong inhomogeneity $\omega_{ni}/\omega_0 \gg 1$ and weak inhomogeneity $\omega_{ni}/\omega_0 \ll 1$. Accordingly, we have

$$(u_{cr})_{\text{strong}} \cong \frac{\omega_{ni}}{\omega_0} V_{cr}, \quad (u_{cr})_{\text{weak}} \cong V_{cr} \,,$$

where,

$$V_{cr} = \sqrt{\frac{\pi}{8}} \, \frac{V_{Te}}{\omega_{ci}} \left(\frac{V_{Ti}}{V_{Td}}\right)^2 \frac{T_i}{T_e} \, \omega_0 \left(\frac{T_e}{T_d}\right)^2 \left(\frac{n_d}{n_e}\right)^2$$

and it is easy to conclude that

$$\frac{(u_{cr})_{\text{strong}}}{(u_{cr})_{\text{weak}}} \cong \frac{\omega_{ni}}{\omega_0} \gg 1 \,. \tag{6}$$

This shows that Buneman instability appears faster in a dusty plasma with weak ion inhomogeneity than in a strong ion one.

For different temperature regimes, Eq. (3) reads

$$u_{cr} = U_{cr} T_1, \quad T_1 = \left(\frac{T_i}{T_e}\right)^{3/2} \gg 1, \quad u_{cr} = U_{cr} T_2, \quad T_2 = \left(\frac{T_i}{T_e}\right)^{3/2} = 1,$$

$$u_{cr} = U_{cr} T_3, \quad T_3 = \left(\frac{T_i}{T_e}\right)^{3/2} \ll 1 \,, \tag{7}$$

where

$$U_{cr} = \sqrt{\frac{\pi m_e}{8 m_i}} \, \frac{\omega_0}{\omega_{ci}} \left(1 + \frac{T_e}{T_d} \frac{n_d}{n_e} \frac{V_{Te}}{V_{Td}}\right)^2 \left(1 - \frac{\omega_{ni}}{\omega_0}\right)^{-1} V_{Ti} \,.$$

At $T_i \gg T_e$, Buneman's instability arrises and leads to the formation of large isolated electrostatic potentials which trap some electrons and dusts to move with ions (e. g., Refs. [13, 14, 33, 38]). However, such instability appears faster in hot electron or isothermal plasma than in hot ion plasma.

Accordingly, the threshold velocity in a dusty plasma satisfies the following inequality for different temperature regimes

$$u_{cr}(T_1 \gg 1) \gg u_{cr}(T_2 = 1) \gg u_{cr}(T_3 \ll 1) \,, \tag{8}$$

i.e., by decreasing the ion temperature with respect to that of electron, the Buneman instability appears faster.

4. *Excitation of instability*

The excitation of Buneman instability put the plasma into a strongly turbulent state. Then a strong turbulent heating of the plasma leads to a rapid increase of the threshold current u_{cr} of the instability up to a value u. Therefore, it will be of great interest to investigate here this instability at current velocities close to the threshold values.

Accordingly, let us consider that the current velocity slightly exceeds the instability threshold, i.e., we set $u = u_{cr} + \Delta u$, where $\Delta u \ll u_{cr}$. As mentioned above, we consider, as usual, a small perturbation in the frequencies and wave numbers (here $\gamma_k,\ \omega_k \neq 0$). After a lengthy calculation, but not complicated, we obtain the following dispersion relation

$$\frac{T_e}{T_i}\frac{1}{\sqrt{2\mu_i}}\frac{\omega_{ni}\Delta\omega}{\omega_0^2}\left(\mathrm{i}Z_{0i}\mathrm{e}^{-Z_{i0}^2}-1\right)+\sqrt{\pi}\,(1-\mu_e)\Re_{0e}\frac{\Delta\omega+ku_{cr}(\theta^2/2)-k\Delta u}{\sqrt{2}\,kV_{Te}}$$

$$+\frac{T_e}{T_i}\frac{1}{\sqrt{2\mu_i}}\left(1-\frac{\omega_{ni}}{\omega_0}\right)\Re_{0i}\frac{\Delta\omega}{\sqrt{2}\,kV_{Ti}}+\sqrt{\pi}\,\frac{T_e}{T_d}\frac{n_d}{n_e}\Re_{0d}\frac{\Delta\omega}{\sqrt{2}\,kV_{Td}}=0\,, \qquad (9)$$

$$\Re_{0\alpha}=\mathrm{i}\mathrm{e}^{-Z_{0\alpha}^2}(1-2Z_{0\alpha}^2)-\frac{1}{\sqrt{\pi}\,Z_\alpha}\,.$$

The dispersion relation (9) yields the growth rate and the frequency (high frequency) of Buneman instability in inhomogeneous dusty plasma for different temperature regimes as follows

$$\gamma_k \cong M_n\sqrt{2\pi\mu_i}\,(1-\mu_e)\left(\frac{\Delta u}{u_{cr}}-\frac{\theta^2}{2}\right)\frac{ku_{cr}}{1+(\Re_1+\Re_2)^2}\left(\Re_1+\sqrt{\omega}\,\Re_2\right), \qquad (10)$$

$$\omega_k \cong \sqrt{\pi}\,Z_{0e}\mathrm{e}^{-Z_{0e}^2}(1-Z_{0e}^2)\gamma_k\,, \qquad (11)$$

where

$$\Re_1=\sqrt{\pi}\,Z_{0i}\mathrm{e}^{-Z_{0i}^2}\left[1-2Z_{0i}^2\left(1-\frac{\omega_{ni}}{\omega_0}\right)\right], \quad \Re_2=\sqrt{\pi}\,Z_{0d}\,\mathrm{e}^{-Z_{0d}^2}\frac{T_i}{T_d}\sqrt{2\pi\mu_i}\,\frac{n_d}{n_e}(2Z_{0d}^2-1)\,.$$

M_n indicates the temperature ratio ($M_n = T_i/T_e,\ n = 1, 2, 3$), i.e., $M_1 \gg 1$, $M_2 = 1,\ M_3 \ll 1$. From (10), conditions of instability are

$$\mu_e<1,\quad \sqrt{2\frac{\Delta u}{u_{cr}}}>\theta,\quad Z_{0i}<\sqrt{\frac{1}{2}}\ \ \left(\text{for }\ \frac{\omega_{ni}}{\omega_0}\ll 1\right),\quad \left(\Re_1+\sqrt{\omega}\,\Re_2\right)>0\,. \qquad (12)$$

The growth rate (10) of Buneman instability in dusty plasma satisfies the following inequality for different temperature regimes

$$\gamma_k(M_1)\gg\gamma_k(M_2)\gg\gamma_k(M_3)\,. \qquad (13)$$

Relation (13) shows that gradual increasing of the electron temperature over that of ions represents a damping of the instability in the linear stage. Besides, dust is affecting strongly Buneman's instability as is clear from the condition $(\Re_1+\sqrt{\omega}\,\Re_2) > 0$ which requires $Z_{0d} > \sqrt{1/2}$.

Let us discuss the growing of instability in two cases: for the strong ion inhomogeneity, i.e., $\omega_{ni}/\omega_0 \gg 1$, then $\Re_1 > 0$, and for the weak ion inhomogeneity, i.e., $\omega_{ni}/\omega_0 \ll 1$, then $\Re_1 < 0$. Accordingly, it is clear from Eq. (10) that a large ion density gradient may be a mechanism to depress such instability.

In both cases, and in the absence of dusts, $\Re_2 \to 0$, and we can check that the presence of dusts plays a crucial role in the growing and damping of Buneman instability, i.e., (i) reduction of growth rate at $2Z_{0d}^2 > 1$, and (ii) increasing the growth rate at $2Z_{0d}^2 < 1$.

5. *Conclusions*

Both the temperature ratio of electrons to ions, in addition to dust, are found to affect strongly the growing or damping of Buneman instability in clean or dusty plasmas. Besides, the dust's grains size and temperature are found to play an important role in controlling this instability: (i) gradual increase of the electron temperature over that of ions leads to a reduction of the growth rate of instability, i.e., in the linear stage, temperature ratio M_n represents a damping mechanisms for instability, (ii) The Buneman instability is found to appear faster in dusty plasma with strong ion inhomogeneity than in weak ion inhomogeneity.

It is found that a large ion density gradient (IDG) may be a mechanism to depress such instability. In both cases (for weak or strong ion inhomogeneity), we can check that presence of dust plays a crucial role in growing or damping of Buneman instability. Experimentally, IDG plays an important role via ion temperature gradient turbulence in DIII-D [39] and the studies of compressed ion temperature gradient turbulence in diverted tokamak edge (L-H transition) [40].

In reality, the temperature and size of dust grains (hence their thermal velocity) are the main parameters controlling such effects on the growth rate γ_k.

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KINETIČKA BUNEMANOVA NESTABILNOST U PRAŠNJAVOJ PLAZMI U RAZLIČITIM TEMPERATURNIM UVJETIMA

Predstavljamo nedavna teorijska istraživanja uzbude Bunemanove nestabilnosti u nehomogenim anizotropnim prašnjavim plazmama. Razmatramo plazme u različitim temperaturnim uvjetima. Izvodimo disperzijsku relaciju i rješavamo 1D Bunemanovu nestabilnost uzbuđenu u takvim plazmama. Nalazimo da su omjer temperature elektrona i iona, stupanj nejednolikosti plazme i toplinska brzina zrnaca prašine ključni za rast i gušenje Bunemanove nestabilnosti.