Modified Simon-Hoh Instability in a Magnetized Inhomogeneous Dusty Plasma

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Abstract The modified Simon-Hoh Instability (MSHI) in an inhomogeneous plasma in presence of charged dust grains is investigated where the ions and dust are unmagnetized but electrons are strongly magnetized. Our dispersion relation matches exactly to the dispersion equation (18) of Sakawa et al., when we withdraw the contribution of dust grains from our expression. The growth rates of MSHI in presence of dust grains, shows either comparable or lower than that of dust free plasma.

1. Introduction:

The interest for studying plasma, with dust particles, is due to realization of their occurrence in both the laboratory as well as in space. The transitions between the low modes of confinement (L-mode) to a high confinement regime (H-mode), in many machines are generally very complicated. In tokamaks, this transition relates to the non-uniform radial electric field at the edges. In plasma fusion process as well as in space and laboratory plasmas, the crossed magnetic and non-uniform electric field is very important for determining the plasma energy flow. The presence of dust particles in the near wall regions of tokamaks is emphasized in connection with problems of higher power loading in future machines. The accumulation of dust particles can considerably influence the heat fluxes and power absorption in the edge tokamak process. The mechanism of the L to H mode transition associated with the edges in the particle flux and the convective energy loss near the plasma edge. Therefore we have investigated the influence of dust particles in a plasma wave in a typical situation, namely in Simon-Hoh instability (SHI). The Simon-Hoh instability is a fluid instability that may occur in a partially ionized non uniform, plasma under a strong radial electric field, perpendicular to the axial magnetic field. Simon, Hoh and Thomassen first analyzed this instability theoretically. The physical mechanism of this instability is caused by the flow speed difference between ions and electrons coupled with plasma gradient. SHI is unstable when density gradient and electric field are in the same direction and is triggered by the difference between electron and ion ExB drift velocities caused by collisions. Sakawa et al. identified Modified Simon-Hoh instability (MSHI) instability similar to collisional SHI. The modified SHI is observed in collisionless cylindrical plasma, produced by a weak electron beam, in which electrons are strongly magnetized and the ions are essentially unmagnetized. The non-linear evolution of this instability occurs through a sequence of sideband instabilities, thought to be induced by trapped ions and lead to turbulent plasma state. The difference between MSHI and SHI are: (a) ions are unmagnetized and electrons are magnetized. (b) Both electrons and ions are collisionless. MSHI occurs due to slower (relative to the electrons) ion drift velocity caused by large ion Larmor radius effect. The smaller ion azimuthal drift velocity compared with the electron ExB velocity cause a charge separation between the electron and ion density perturbations in the θ direction. The resulting azimuthal electric field Ex and the enhancement of the density perturbation occur in the same manner as in the case of SHI. When the ion flow speed of plasma is much smaller than the ExB speed in a strongly double sheared electric field, the stability is investigated. When the ion drift speed is assumed to be identical to the ExB drift speed, Kelvin-Helmholtz (KH) instability becomes most probable instability to excite and also it is the most well known instability associated with sheared flow of the density gradient which lowers the growth rate of the excited wave. Finite temperature makes the KH mode unstable while finite Larmor radius (FLR) effect tends to stabilize the KH instability in the low wavelength range. Instability, in our case arises...
when the ion flow speed is different from the ExB speed and is therefore completely different from the KH mode. This somewhat different instability is identified as collisionless SH instability or MSHI. The evolution of this instability occurs through a sequence of sideband instabilities thought to be induced by trapped ions and a period of doubling space. The earlier work on this topic considered plasma that contains electrons, ions and neutral particles. But in our work, we have considered dust particles as an additional component in quasi-neutral plasma. The presence of dust grains significantly affects the behavior of plasma in which they are immersed. Therefore, MSHI in magnetized inhomogeneous dusty plasmas may be important in laboratory plasma experiments, plasma fusion research and astrophysical environment.

In this paper, we have investigated MSHI in inhomogeneous magnetized plasma with dust grains. First, we frame the governing equations (momentum and continuity) for the plasma particles. Next, we derive the dispersion relation. From our dispersion relation we numerically solve the growth rate and compared it with the result of Sakawa et al.\textsuperscript{15}. Finally we discussed the obtained results.

2. Basic governing equations

We consider inhomogeneous magnetized dusty plasma consisting of electrons, ions and massive point charged dust particles under the influence of electric field perpendicular to the magnetic field. The basic equations of motion and the continuity equations for the ions, electrons and dust species are given by,

\[ m_\alpha n_\alpha \partial_\tau V_\alpha + m_\alpha n_\alpha (V_\alpha \cdot \nabla)V_\alpha - q_\alpha n_\alpha (E + V_\alpha \times B) - T_\alpha \nabla n_\alpha - m_\alpha n_\alpha V_\alpha V_\alpha = 0 \]  \hspace{1cm} (1)

\[ \partial_\tau n_\alpha + \nabla \cdot (n_\alpha V_\alpha) = 0 \]  \hspace{1cm} (2)

where, \( \alpha = \text{i (ion), e (electron) and d (dust species).} \) \( q_{i,e} = \pm e, \ q_{d} = Z_d e. \) \( q_{i,e} \) represents the charge. \( Z_d \) is the charge number for the dust species. \( \nabla_\alpha \) is the collision frequency of the given species with neutrals. In the momentum equation (1) \( V_\alpha, n_\alpha \) and \( m_\alpha \) are the velocity, density and mass of any species. The electric field and magnetic field are given by \( E = E \hat{x}, \ B = B \hat{z} \) respectively. \( \phi \) is the fluctuating potential and perturbed density is \( \tilde{n}_\alpha \) of any species. \( T_\alpha \) is the temperature while charge of an electron is \( e. \)

3. Dispersion Relation

To linearize fluid equations, we assume all perturbed quantities to vary as proportional to \( \exp(i(kr - \omega t)) \). The expression for the perturbed density, following Ref.15, can be written as

\[
\frac{\tilde{n}_\alpha}{n_\alpha} \approx \frac{q_\alpha \phi}{m_\alpha} \left\{ \frac{k_y^2}{\omega_\alpha^2 - \Omega_\alpha^2} + \frac{k_z^2}{\omega_\alpha^2 + i\nu_\alpha \omega_\alpha} \right\} \left(1 - \frac{T_\alpha}{m_\alpha} \left( \frac{k_y^2}{\omega_\alpha^2 - \Omega_\alpha^2} + \frac{k_z^2}{\omega_\alpha^2 + i\nu_\alpha \omega_\alpha} + \frac{k_{na}^2 - \Omega_\alpha k_{na} k_y}{\omega_\alpha^2 - \Omega_\alpha^2} \right) \right\}^{-1}
\]  \hspace{1cm} (3)
where, \( \vec{\alpha}_\alpha = \omega - k \cdot V_{\alpha 0} \), \( V_\omega \) is the drift term. \( k \alpha = \left| \frac{1}{\eta e_0} \frac{dn_{\alpha 0}}{dx} \right| \) is the density gradient. The general expression for cyclotron frequency is 

\[
\Omega_{\alpha} = \frac{\eta B}{m_{\alpha}} \]

\( k_y, k_z \) are the wave number in the y and z direction. Now, we consider y as \( \theta \) and x as \( r \) in cylindrical co-ordinate system to get the density perturbation of each species considering the following plasma approximations:

(i) Ions and dust particles are unmagnetized i.e. \( \Omega_i < \Omega_d < \Omega_e < \Omega_\phi \), where \( C_e = \sqrt{\frac{T_e}{m_e}} \)

(ii) Ions and dust particles are cold while plasma electrons are not cold \( (T_i, T_d = 0, T_e \neq 0) \)

(iii) Collision frequency for ions, electrons and dust particles with neutral particles are negligible, i.e. \( (V_{in}, V_{en}, V_{dn} = 0) \) and (iv) \( k_{ne} \gg k_\phi > k_z, k_{ni}, k_{nd} \) as

\[
\bar{n}_e = \frac{e \phi}{n_{e0}} \frac{\omega^*}{T_e} \frac{\omega - \omega_E}{\omega}
\]

\[
\bar{n}_i = \frac{e \phi}{n_{i0}} \frac{C_i^2 k_\phi^2}{T_e \left( \omega - \omega_k \right)^2}
\]

\[
\bar{n}_d = \frac{e \phi}{n_{d0}} \frac{C_D^2 k_\phi^2}{T_e \omega^2}
\]

\[
C_s = \sqrt{\frac{T_e}{m_i}} \text{ and } C_D = \sqrt{\frac{Z_d T_v}{m_d}}
\]

\( C_s, C_i, C_e \) and \( C_\phi \) denote acoustic speed of electron, ion and dust particles respectively. \( \omega^* = k_\phi V_{ed} \) is the electron diamagnetic drift frequency, \( \omega_E = -k_\phi E_{r0} / B_0 \) is the electron \( E \times B \) drift frequency, \( \omega_\phi = V_\phi k_\phi \) is the azimuthal ion drift frequency, where \( k_\phi \) is wave number in azimuthal direction.

Quasi neutrality leads to

\[
\bar{n}_i = \bar{n}_e + Z_d \bar{n}_d
\]

Considering \( a = \frac{n_{i0}}{n_{e0}} \), \( b = \frac{Z_d n_{d0}}{n_{e0}} \) and using equations (4), (5), (6) and (7) we get the following dispersion relation as:

\[
\frac{a \omega_{pi}^2}{(\omega - \omega_k)^2} = \frac{\omega^*}{k_\phi^2 \lambda_D^2 (\omega - \omega_E)} + \frac{b \omega_{pd}^2}{\omega^2}
\]

where, \( \omega_{pi, pe} \) is the plasma frequency and \( \lambda_0 \) is the Debye length.

The real frequencies,

\[
\omega_1 = k_\phi V_{\theta} + \frac{k_\phi^2 \left[ a C_s^2 - b C_D^2 \right]}{2 \omega^*}
\]
The expression given by equation (9) exactly matches with the result obtained by Sakawa et al.\textsuperscript{15} [equation no. (19)], if we neglect the contribution of the dust particles from the above equation (9). Therefore, the contribution of dust particles to MSHI can be controlled. The other low mode real frequency is represented by equation (10).

The growth rate of MSHI in inhomogeneous magnetized dusty plasma can be obtained as from (equation 8). The high and low frequency of growth rates is given in equation (11) and (12) respectively.

\[
\omega_1 = \frac{k_\theta V_{\theta 1}}{\sqrt{2\omega^*}} \left[ aC_s^2(\omega_E - \omega_1) + \frac{abk_\theta^2C_s^2C_s^2}{2\omega^*} - bC_D^2(\omega_E + \omega_1) - \frac{k_\theta^2}{4\omega^*}(b^2C_D^4 - a^2C_s^4) \right]^{1/2}
\]

\[
\omega_2 = \frac{1}{2} \left[ \begin{array}{c}
\omega_{\theta 1}^2(\omega_E - \omega_{\theta 1}) + 4b^2k_\theta^2C_D^2 \left[ bC_D^2k_\theta^2(\omega_E - \omega_{\theta 1}) - \omega_E\omega_1\omega_1 + ak_\theta^2C_s^2 \right] \\
+ 2aC_s^2k_\theta^2(\omega_E - \omega_{\theta 1}) - bC_D^2k_\theta^2(\omega_E - 2bC_D^2k_\theta^2\omega_{\theta 1} - 2\omega_1^2bC_D^2k_\theta^2(\omega_E + 2\omega_{\theta 1})) \end{array} \right]^{1/2}
\]

4. Numerical Results

In our numerical calculation, we choose the parameters of the experiment of Sakawa et al\textsuperscript{15}. These are given by \(n_i = 1 \times 10^9 \text{ cm}^{-3}\), \(n_e = 1 \times 10^8 \text{ cm}^{-3}\), \(T_e = 4\text{ eV}\), \(C_s = 3.1 \times 10^5 \text{ cm s}^{-1}\), \(\omega^* = 1.9 \times 10^7 \text{ s}^{-1}\) and \(\omega_E = 3.9 \times 10^6 \text{ s}^{-1}\). The dust parameters to be used are \(Z_d = 100\), \(n_d = 10^6 \text{ cm}^{-3}\) and \(m_d = 4 \times 10^{-16} \text{ g}\).

Figure 1 Growth rate \(\omega\) versus wave number in \(\Theta\) direction \(k_\theta\). \(--\) represents high frequency results, \(--\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\right computation of the other low mode real frequency is represented by equation (10).

\[
\omega_2 = \frac{1}{2} \left[ \begin{array}{c}
\omega_{\theta 1}^2(\omega_E - \omega_{\theta 1}) + 4b^2k_\theta^2C_D^2 \left[ bC_D^2k_\theta^2(\omega_E - \omega_{\theta 1}) - \omega_E\omega_1\omega_1 + ak_\theta^2C_s^2 \right] \\
+ 2aC_s^2k_\theta^2(\omega_E - \omega_{\theta 1}) - bC_D^2k_\theta^2(\omega_E - 2bC_D^2k_\theta^2\omega_{\theta 1} - 2\omega_1^2bC_D^2k_\theta^2(\omega_E + 2\omega_{\theta 1})) \end{array} \right]^{1/2}
\]

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5. Conclusions

We have investigated an electrostatic instability at an intermediate frequency i.e. $\Omega_I < \omega < \omega_e$ in an inhomogeneous collisionless magnetised dusty plasma. We have identified a different kind of instability due to the presence of dust grains in plasma, which is similar to the MSHI. This MSHI has a similar instability mechanism to that of the Simon-Hoh instability and it occurs only when the density gradient is in the direction of the radial dc electric field. The phase velocity of this instability is decided by ion azimuthal drift velocity, or the $E\times B$ drift velocity. With ion FLR, the effect of dust grains in the collisionless inhomogeneous magnetized plasma excites the MSHI such that its growth rate becomes either comparable or lower than that observed in dust free plasma (Fig. 1). One reason for this instability to grow may be through a sequence of sideband instabilities due to trapped ions and dust grains. The other way may be due to period doubling sequence. It is still not clear why the system chooses one path to nonlinear evolution over another. Therefore, we, with the help of our model, may trace the development of plasma turbulence from first principle and therein the effect of dust grains.

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