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# Surface waves at the interface of a dusty plasma and a metallic wall

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Electrostatic surface waves at the interface between a low-temperature nonisothermal dusty plasma and a metallic wall are investigated. The plasma contains massive negatively charged impurity or dust particles. It is shown that the impurities can significantly alter the characteristics and damping of the surface waves by reducing their phase velocity and causing charging-related damping. [S1063-651X(98)03608-3]

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## I. INTRODUCTION

Recently there has been much interest in impurity and dust particles in low-temperature plasmas. Such particles can appear as a result of erosion of the confining wall in fusion devices [1,2]; they are also inherently released in plasma-assisted material processing such as etching or polishing or they can be polymerized in the gaseous phase [3–6]. Because of their heavy charge and mass, the dusts can strongly affect the plasma properties and cause disruption or breakdown in some industrial processes. It is thus often desirable that the dust grains be controlled or removed from the operating plasma volume. In fusion devices the impurities can be removed by divertors. In industrial processes they are deposited off the substrate or blown off by gas or plasma streams. In all the processing and dust removal schemes a stringent control of the dust dynamics is crucial. Such control can be realized by, for example, externally applied electromagnetic fields and/or the fields of the natural eigenmodes of the waveguide structure. It is therefore important to understand the natural and driven surface waves in a dusty plasma.

In the literature on the collective phenomena in dusty plasmas much attention has been paid to the volume, or bulk, waves in infinite plasmas. It is found [7–12] that the dusts can strongly affect the eigenmodes by causing frequency shifts, anomalous dampings, instabilities, etc. On the other hand, surface waves (SWs) at the boundary between dusty plasmas and metallic walls [13] have not been considered. The problem is of practical interest since such interfaces are unavoidable in the plasma processing of metal surfaces [6] as well as at the limiters and divertors in fusion devices [1]. Furthermore, SWs in plasma-metal structures can be used for the production and sustainment of rf and microwave discharges employed for material processing [14]. As the SWs possess a tangential electric field component whose magnitude is of the same order as that of the normal component, their electromagnetic fields can be used for the drive and control of ion and dust flows. The latter are crucial in controlling the dust and impurity problems in many discharge configurations in technological processes as well as in fusion systems (limiters and divertors) where the presence of dust and impurity particles is unavoidable.

In this paper we investigate the electrostatic surface eigenmodes at the interface between a low-temperature dusty plasma and a metal surface. The linear dispersion relations are obtained for both constant and variable dust charges. It is shown that for typical discharges used in the applications, the impurities can significantly affect the surface wave properties.

## II. CONSTANT DUST CHARGE

We investigate the effect of dust (impurity) particles on the dispersion characteristics and damping of electrostatic SW propagating at the interface between a dusty plasma and a metallic wall. Two cases, for dusts with constant charge and dusts with variable charge determined by the coupling of the dust-charge relaxation process and the SWs, are considered.

It is instructive to first consider the electrostatic potential distribution and the dispersion properties of electrostatic SW in plasmas containing constant-charge dust particles or impurity ions. We assume that the isotropic plasma with thermal electrons is bounded at $x=0$ by a metal surface, which is assumed to be perfectly conducting. The plasma contains massive dust grains with an average constant charge $q_d=-|Z_d|e$, where $e$ is the magnitude of the electron charge. The dust charge is negative since the dust grain tends to collect many more electrons, which are much more mobile than the ions because of their small mass. The dust size is much smaller than the electron Debye length and the distance between the plasma particles. Thus one can treat the dust grains as massive (compared to the plasma ions) point masses with constant negative charge. The finite pressure of the electron gas shall be taken into account and the plasma is assumed to be strongly nonisothermal ($T_e \gg T_i, T_d$). The linearized equations describing the oscillations can then be written as

$$\partial_t n_j + \vec{\nabla}\cdot(n_{0j}\vec{v}) = 0, \tag{1}$$

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$$\partial_t \vec{v}_j + \nu_j \vec{v}_j = (q_j/m_j)\vec{E} - V_{Tj}^2 \vec{\nabla} n_j / n_{0j}, \tag{2}$$

$$\vec{\nabla}\cdot\vec{E} = 4\pi \sum_j q_j n_j, \tag{3}$$

where the subscript $j=e,i,d$ denotes the electron, ion, and dust quantities; $m_j$, $q_j = Z_j e$, $Z_j$, $n_{0j}$, $n_j$, $\vec{v}_j$, and $V_{Tj}$ are the mass, charge, charge number (including the sign), unperturbed and perturbed densities, and hydrodynamic and thermal velocities, respectively; and $\vec{E}$ is the electric field of the SW. In the unperturbed state the quasineutrality condition $Z_i n_{i0} = n_{e0} + Z_d n_{d0}$ is satisfied. Considering electrostatic perturbations ($\vec{E} = -\vec{\nabla}\phi$, where $\phi$ is the electrostatic potential) propagating in the $z$ direction and assuming that the waves behave like $\exp[i(k_z z - \omega t)]$, we can easily derive

$$n_e = (\epsilon_{id}/4\pi e)\nabla^2\phi, \tag{4}$$

$$\vec{v}_e = \frac{ie}{m_e(\omega + i\nu_e)}\,[\vec{\nabla}\phi - r_{\mathrm{De}}^2 \vec{\nabla}(\epsilon_{id}\nabla^2\phi)], \tag{5}$$

where $\epsilon_{id} = 1 + \chi_i + \chi_d$, $\chi_j = -\omega_{pj}^2/\omega(\omega + i\nu_j)$, $\omega_{pj}^2 = 4\pi e^2 Z_j^2 n_{j0}/m_j$, $\nu_j$ are the effective collision frequencies, and $r_{\mathrm{De}}$ is the electron Debye length.

Substituting Eqs. (4) and (5) into Eq. (1) for the electrons, one obtains for the SW electrostatic potential

$$\left[\epsilon + \frac{v_{Te}^2}{\omega(\omega + i\nu_e)}\vec{\nabla}\cdot\epsilon_{id}\vec{\nabla}\right]\nabla^2\phi = 0, \tag{6}$$

where $\epsilon = \epsilon_{id} + \chi_e$. Equation (6) is a fourth-order differential equation and it yields the following solution for the plasma $(x>0)$:

$$\phi(x) = A_1 \exp(-k_z x) + A_2 \exp(-\kappa x), \tag{7}$$

where $A_1$ and $A_2$ are constants and $\kappa^2 = k_z^2 - \epsilon\omega(\omega + i\nu_e)/V_{Te}^2\epsilon_{id}$. We note that Eq. (7) implies that there are two characteristic SW skin depths, namely, $\lambda_1 = k_z^{-1}$ and $\lambda_2 = \kappa^{-1}$. That is, in a plasma with finite electron pressure the electric field of the SW consists of a superposition of the fields $A_1$ and $A_2$ due to electrostatic and (electron) thermal effects, respectively. The field $A_1$ is localized within the region $x \lesssim \lambda_1$ and it usually defines the value of the SW field in the plasma volume. The localization region of field $A_2$ is significantly less, that is, $\lambda_1 \gg \lambda_2$, since $\lambda_2$ is usually of the order of several Debye lengths and $\lambda_1$ is of the order of a wavelength. Although the thermal part of the SW field is negligible in the plasma bulk, it is important for the electrostatic potential near the interface [13]. The solution (7) vanishes for $x \to \infty$.

To obtain the dispersion relation of the SW, two boundary conditions are necessary [15,16]. One of them is obtained directly from Eq. (6) by integrating it over a narrow interface layer $x = [-\sigma, \sigma]$ with $\sigma \to 0$ or

$$\phi(x=0) = 0, \tag{8}$$

so that the tangential component of the electric field vanishes at the plasma-metal interface.

The second boundary condition can be the vanishing of the normal component of the electron fluid velocity in the SW field at $x=0$ or $v_{ex}(x=0)=0$. This boundary condition is widely used for describing bounded plasmas and is of good accuracy for well-polished dielectric or metal surfaces [15,16]. In terms of the SW potential, we have

$$\partial_x[(1 - r_{\mathrm{De}}^2\epsilon_{id}\nabla^2)\phi]_{x=0} = 0 \tag{9}$$

as the second boundary condition.

Using the boundary conditions (8) and (9), the solution (7) leads to the dispersion relation

$$k_z = \kappa(\omega/\omega_{pe})^2, \tag{10}$$

where the collisional losses are neglected. Here, analogous to the dust-free case [13,17], the SWs exist in the frequency regime $\omega_{pi}^2 < \omega^2 \ll \omega_{pe}^2$. Moreover, the skin depths $\lambda_1$ and $\lambda_2$ satisfy $\lambda_1 \gg \lambda_2 \sim r_{\mathrm{De}}\sqrt{\epsilon_{id}}$. The SW eigenfrequency can then be expressed as $(\omega/\omega_{pe})^2 = k_z r_{\mathrm{De}}\sqrt{\epsilon_{id}}$. We also note that $V_{\mathrm{ph}}/V_{Te} \sim \omega/\omega_{pe}\sqrt{\epsilon_{id}}$, where $V_{\mathrm{ph}}$ is the wave phase velocity. In the limit $n_d = 0$ the corresponding dust-free dispersion relations [13,17] are recovered.

For plasmas containing negatively charged dusts the electron density can be lowered compared to the dust-free case by a factor $\gamma \equiv [1 + (n_{d0}/n_{e0})Z_{d0}]^{1/2}$. This implies that the SW wave number $k_z$ will be larger, corresponding to a decrease of $V_{\mathrm{ph}}$. This decrease of the wave phase velocity in turn leads to the possibility of a more effective interaction between the SWs and the plasma particles in the gas discharge. It also causes more prominent realization of the nonlinear effects, since the efficiency [18,19] of the latter is proportional to $V_E/V_{\mathrm{ph}}$, where $V_E$ is the electron oscillation frequency in the wave field. In the presence of dust particles the electric skin depth $\lambda_1$ decreases and the thermal skin depth $\lambda_2$ increases.

### III. EFFECT OF CHARGE VARIATION

We now consider the effect of the dust-charge variation on the SW at time scales comparable to the SW period. The dust-grain charge is assumed to vary according to the microscopic electron and ion currents entering the dust grain. These currents are caused by the potential difference between the grain surface and the adjacent plasma. Since the time scales of dust charging and the SW are much smaller than that of the dust motion, the dust grains shall be taken as immobile. The basic assumptions and governing equations are the same as for Sec. III, except that now the dust charge $q_d$ is no longer constant. For simplicity, the effect of collisions shall be ignored, as it can be added in the final dispersion relation. The electron, ion, and and dust grain temperatures satisfy $T_e \gg T_i, T_d$. To be consistent with the dust charging model, the ion temperature shall be treated as finite. However, the characteristic velocities of the process studied are much higher than $V_{Ti}$.

The process of dust charging is described by [8–10]

$$d_t q_d = I_e(q_d) + I_i(q_d), \tag{11}$$

where $q_d$ is the average charge on the dust grain and $I_e(q_d)$ and $I_i(q_d)$ are the electron and ion grain currents. The dust quantities $q_d$, $I_e$, and $I_i$ are perturbed such that $q_d = q_{d0} + q_{d1}$ and $I_{(e,i)} = I_{(e,i)0} + I_{(e,i)1}$. The stationary dust charge is given by $q_{d0} = C(\phi_g - \phi_0)$, where $C = a(1 + a/r_{\mathrm{De}})$ is the grain capacitance, $a$ is the particle radius, and $\phi_g - \phi_0$ is the steady-state potential difference between the grain and the adjacent plasma.

The stationary electron and ion currents flowing into the grain can be written as [8–10]

$$I_{e0} = -\pi a^2 e (8T_e/\pi m_e)^{1/2} n_{e0} \exp[e(\phi_g - \phi_0)/T_e], \tag{12}$$

$$I_{i0} = \pi a^2 e Z_i (8T_i/\pi m_i)^{1/2} n_{i0} [1 - e(\phi_g - \phi_0)/T_i], \tag{13}$$

which are equal in the unperturbed state and also define the floating potential $\phi_0$. The perturbed dust charge is governed by

$$d_t q_{d1} + \nu_{\mathrm{ch}} q_{d1} = -|I_{e0}| n_{e1}/n_{e0} + |I_{i0}| n_{i1}/n_{i0}, \tag{14}$$

where

$$\nu_{\mathrm{ch}} = e|I_{e0}| \left( \frac{1}{CT_e} + \frac{1}{CT_i - e q_{d0}} \right) \tag{15}$$

is the grain-charging rate [9,10]. Here the perturbation ion current caused by the low-frequency surface wave is to be calculated from the two-fluid theory, which for the case considered is appropriate since the phase velocity of the SW significantly exceeds $V_{Te}$ and $V_{Ti}$ [20]. For lower SW phase velocities more accurate expressions can be obtained from kinetic approaches [8,21].

From Eqs. (1)–(3) we obtain the perturbed electron and ion densities

$$n_{e1} = (\epsilon/4\pi e) \nabla^2 \phi - Z_{d1} n_{d0}, \tag{16}$$

$$n_{i1} = -Z_i e n_{i0} \nabla^2 \phi, \tag{17}$$

where $\epsilon_i = 1 - \omega_{pi}^2/\omega^2$, $\omega_{pi}$ is the ion plasma frequency, and $Z_{d1} = q_{d1}/e$ is the perturbation dust-charge number. Substituting Eqs. (16) and (17) into Eq. (14), one obtains the dust charge relaxation equation

$$d_t q_{d1} + \nu_{\mathrm{ch}}^* q_{d1} = -\frac{|I_{e0}| \epsilon_i'}{4\pi e n_{e0}} \nabla^2 \phi, \tag{18}$$

where $\nu_{\mathrm{ch}}^* = \nu_{\mathrm{ch}} + \alpha$ is the dust-charging frequency, which includes the correction due to the electron density perturbation, $\alpha = |I_{e0}| n_{d0}/e n_{e0}$, and $\epsilon_i' = 1 - (\omega_{pi}^2/\omega^2)(1 - 1/\gamma^2)$.

From Eqs. (18) and (17) it is easy to obtain the expressions for the dust charge, electron density, and the fluid velocity

$$q_{d1} = -\frac{i|I_{e0}| \epsilon_i' \nabla^2 \phi}{4\pi e n_{e0}(\omega + i\nu_{\mathrm{ch}}^*)}, \tag{19}$$

$$n_e = (\epsilon_{id}'/4\pi e) \nabla^2 \phi, \tag{20}$$

$$\vec{v}_e = i(e/m_e \omega)[\vec{\nabla}\phi - r_{\mathrm{De}}^2 \vec{\nabla}(\epsilon_{id}' \nabla^2 \phi)], \tag{21}$$

where $\epsilon_{id}' = \epsilon_i [1 - i\alpha \epsilon_i'/\epsilon_i(\omega + i\nu_{\mathrm{ch}}^*)]$. From the electron continuity equation (1) one obtains for the SW electrostatic potential

$$[\epsilon' + (v_{Te}^2/\omega^2) \nabla^2 \epsilon_{id}'] \nabla^2 \phi = 0, \tag{22}$$

where $\epsilon' = \epsilon - i\alpha\epsilon_i'/(\omega + i\nu_{\mathrm{ch}}^*)$ and $\epsilon = \epsilon_i - \omega_{pe}^2/\omega^2$. Equation (22) also admits as a solution expression (7), but with $\kappa$ replaced by $\kappa'$, where $\kappa'^2 = k_z^2 - \epsilon' \omega^2/\epsilon_{id}' v_{Te}^2$. The dispersion relation for SWs at the plasma-metal interface for the variable dust charge case is then $k_z = \kappa'(\omega/\omega_{pe})^2$.

The general dispersion relation for the coupled SWs and the dust-charge relaxation mode can be written as

$$(\omega^4 - k_z^2 V_{Te}^2 \omega_{pe}^2 \epsilon_i)(\omega + i\nu_{\mathrm{ch}}^*) = -i\alpha k_z^2 V_{Te}^2 \omega_{pe}^2, \tag{23}$$

which also describes the coupling between the two modes. The solutions of Eq. (23) for the SWs ($\omega_{1,2}$) and the purely damped dust-charging mode ($\omega_3$) are

$$\omega_{1,2} = (|k_z| V_{Te} \omega_{pe})^{1/2} \epsilon_i^{1/4} (1 - \alpha \nu_{\mathrm{ch}}^* \mathcal{A}) - i\alpha |k_z| V_{Te} \omega_{pe} \epsilon_i^{1/2} \mathcal{A}, \tag{24}$$

where $\mathcal{A}^{-1} = 4\epsilon_i (\nu_{\mathrm{ch}}^{*2} + |k_z| V_{Te} \omega_{pe} \epsilon_i^{1/2})$, and

$$\omega_3 = -i(\nu_{\mathrm{ch}} - \alpha \nu_{\mathrm{ch}}^{*4} \mathcal{B}), \tag{25}$$

where $\mathcal{B}^{-1} = k_z^2 V_{Te}^2 \omega_{pe}^2 \epsilon_i - \nu_{\mathrm{ch}}^{*4}$.

Similar to the constant dust-charge case, the SWs acquire a frequency downshift due to the presence of dust. However, there is also an additional damping of the SWs because of a coupling to the charge relaxation mode. Furthermore, the expression for the latter mode also suggests that the charging rate $\nu_{\mathrm{ch}}$ decreases when $\omega > \nu_{\mathrm{ch}}^*$ and increases if the opposite inequality holds. However, numerical estimates show that the inequality $\omega > \nu_{\mathrm{ch}}^*$ is usually realized because generally the SW eigenfrequencies are larger than $\omega_{pi}$ and $\nu_{\mathrm{ch}}^*$ is significantly less than $\omega_{pi}$.

## IV. APPLICATIONS

We now estimate the effect of the dust grains on the SW phase velocity using typical parameters for dust-containing plasmas. For the case studied we have $V_{\mathrm{ph}} \propto n_{e0}^{1/2} \propto \gamma^{1/2}$, where $\gamma^{1/2}$ is the relative variation of the wave phase velocity with respect to the dust-free case. For the estimates we take two sets of parameters that are relevant to rf plasma-assisted deposition processes and gas-target divertors, respectively.

For plasma-assisted deposition processes we have [22] $n_{d0} \sim 2 \times 10^5$ cm$^{-3}$, $n_{e0} \sim 10^9$ cm$^{-3}$, $SiO_2$ particles with $a \sim 5$ $\mu$m, $T_e \sim 2$ eV, and $T_i \sim 0.3$ eV, for a rf discharge with the frequency $\omega/2\pi \sim 13.56$ MHz in an argon plasma. To estimate the charge of the dust grains we use $-Z_d e = (\phi_g - \phi_0) a (1 + a/r_{\mathrm{De}})$, which is valid for a conducting sphere [23] in the electrostatic approximation. Assuming $\phi_g - \phi_0 \sim 10$ V and noting that $a \ll r_{\mathrm{De}}$, we have $Z_d \sim 7 \times 10^4$. Taking into account that the charge of the real (usually dielectric and not perfectly conducting) dust grain is less than that given by the electrostatic approximation [5], for the numerical estimates we take the slightly lower value $Z_d \sim 5 \times 10^4$. Under these conditions we have $\gamma = [1 + (n_{d0}/n_{e0}) Z_d]^{1/2} \approx 3.32$. Therefore, the SW phase velocity is approximately

1.8 times lower than in the dust-free case. It should be noted that the analogous effect for ion-acoustic SWs at a dusty plasma-dielectric interface is $\gamma^{1/2}\sim 1.8$ times higher [24]. Moreover, if we assume $a\sim 1\ \mu$m, then $Z_d\sim 10^4$ and $\gamma \sim\sqrt{2}$. In this case the SW phase velocity would be 1.19 times lower than in dust-free plasmas. That is, smaller dust grains have less effect on the SW properties.

Typical parameters for a gas-target divertor configuration [25] are $T_e\sim 20$ eV, $T_i\sim 3$ eV, $n_{e0}\sim 2\times 10^{12}$ cm$^{-3}$, $H_0 \sim 0.15$ T, $a\sim 5\ \mu$m, and $n_{d0}\sim 10^9$ cm$^{-3}$. One then obtains for the SW phase velocity a factor 2.26 decrease. Therefore, dust particles can also affect the physical processes near the divertors of fusion devices.

## V. DISCUSSION

It is still necessary to justify the weak coupling approximation $\omega\gg\alpha$ used in the derivation of the dispersion relations. The equilibrium grain charge $q_{d0}=-|Z_{d0}|e$ can be deduced from a balance of the stationary electron (12) and ion currents (13) flowing into the grain. This balance leads to

$$\exp\left(\frac{eq_{d0}}{CT_e}\right)=\frac{n_{i0}}{n_{e0}}\left(\frac{T_i m_e}{T_e m_i}\right)^{1/2}\left(1-\frac{eq_{d0}}{CT_i}\right), \qquad (26)$$

which yields $q_{d0}$.

For nitrogen plasmas with $T_e\sim 10$ eV, $T_e/T_i\sim 10$, $n_{i0} \sim 10^{11}$ cm$^{-3}$, $n_{e0}\sim 5\times 10^{10}$ cm$^{-3}$, and $a\sim 5\ \mu$m one obtains $eq_{d0}/CT_e=(e/T_e)(\phi_g-\phi_0)\sim -2.35$, which leads to the stationary value of the grain charge $q_{d0}=-2.35(T_e/e)a$. We then have $Z_{d0}=q_{d0}/e\sim -9\times 10^4$ and $\alpha\sim 8 \times 10^6$ sec$^{-1}$. Thus the basic assumption about the weakness of the coupling between the SW and the dust charge relaxation mode is easily satisfied for the typical SW-generator frequency $f=13.56$ MHz (or $\omega=8.5\times 10^7$ sec$^{-1}$).

The dust-charging rate $\nu_{\rm ch}$ is also significantly less than the SW eigenfrequency for the same set of parameters. In fact, we have $\nu_{\rm ch}\sim 2.5\times 10^7$ sec$^{-1}$. For the alternative typical rf generator frequency $f=40.68$ MHz, we have $\omega/\nu_{\rm ch} \sim 10.2$. Thus, in the expressions for the SW frequency shift the terms proportional to $\nu_{\rm ch}^{*4}$ can be neglected. The numerical estimates also suggest that for the typical low-temperature laboratory plasmas [9] the micrometer-sized dust grains have an average charge of $-10^4 e$.

## VI. CONCLUSION

To summarize, in this paper we have considered the effect of massive and heavily charged dust particles on the propagation of SWs at the interface between a warm plasma and a perfectly conducting metallic wall. It is shown that under certain conditions the effect of dust grains in a plasma can be quite important. In general, the dust causes a reduction of the SW phase velocity and a dust-charging-induced wave damping. When the dust charge can be treated as constant, the phase velocity of the SWs in dusty plasmas is less than that of the dust-free case with the same parameters. When the dust-charge variation is taken into account, a coupling between the wave and the dust-charge variation process takes place. This coupling leads to a frequency downshift as well as an additional damping of the SWs. The damping can be comparable to the collisional damping. It is also found that larger dust grains can affect the properties of SWs more strongly. These phenomena can have a significant impact on SW produced and maintained plasmas that are often used in the industry. In particular, the decrease in the wave phase velocity leads to the possibility of a more effective interaction of the SW with the plasma particles. Such an interaction is essential for the efficient operation of SW produced and sustained discharges. For the same reason, similar effects can be expected for the divertor configurations. On the other hand, there are still many factors, such as the structure of the near-wall plasma sheath, shielding of the dust grains, reliability of the present dust charging model, and size and mass distributions of the dust grains, that could also affect the SW properties and have not been accounted for. More detailed theoretical and experimental studies of SWs at the dusty plasma-metal structure interface are therefore warranted.

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