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Dust density effect on complex plasma decay

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Abstract

In this paper, the influence of dust particles on the plasma losses in a complex plasma afterglow is studied. It is shown that the dust particles can drastically shorten the plasma loss time by absorption-recombination onto their surfaces. The dust particle absorption frequency increases with the dust density but the dependence is not linear for high dust density. Finally, the possible use of dust absorption frequency measurements as a diagnostics for complex plasmas is mentioned and supported by comparison to existing experimental data.

Key words: Complex plasma, dust, afterglow, decay

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1. Introduction

Complex plasmas (also called dusty plasmas) are partially ionised gases in which there are charged dust particles. They can be natural plasmas (such as near-Earth plasmas, combustion plasmas, comet tails, planetary rings, interstellar clouds, etc) or human-made plasmas (PECVD, etching, fusion reactor, etc). The dust particles are charged due to their interactions with the surrounding plasma electrons and ions [1,2]. The presence of this new charged species leads to interesting phenomena that distinguish complex plasma from classic dust-free plasma [3–5].

In laboratory discharges, the dust particles can be either grown directly in the plasma chamber (by sputtering [6,7] or using reactive gases [8,9]) or injected inside the plasma [10,11]. Due to a higher mobility of the electrons the dust particles are negatively charged. Consequently, in running discharges, dust particles act as a sink for the electrons of the plasma [2].

The loss of charged species in a complex plasma afterglow is of major importance as it determines the charge carried by the dust particles during the decay process and is fundamental to explain the dust particle residual charges observed experimentally in the late afterglow [12,13]. Dust particle residual charge can be useful (for example, the cleaning of industrial or fusion reactors using electrostatic

techniques) or harmful (for example, future single electron devices where residual charge on deposited nanocrystal would be the origin of malfunction).

In a complex plasma afterglow, the dust particles will increase the plasma losses as ion and electron absorption-recombination can occur at their surface. When the dust particle density is high the particle absorption time τ_Q decreases. The plasma decay time τ_L can thus be drastically shortened. This effect has been observed by Dimoff and Smy in 1970 [14] but their results were not properly explained, especially the effect of high dust density on the particle absorption frequency that was far from their theoretical prediction.

In this paper, the influence of dust particle density on plasma losses due to recombination on to dust particle surfaces is discussed. It is shown that the dust particle absorption frequency does not grow linearly with the dust density. This effect is visible when the ratio of the total charge carried by the dust particles to the charge carried by the ions (Havnes parameter) is close to 1. Finally, by comparison of the model with existing experimental data, the possibility of using plasma decay time in a complex plasma as a diagnostic is discussed.

2. Theoretical approach

When a discharge is switched off, the ions and electrons of the plasma start to diffuse and the plasma density decreases

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as follows:

$$\frac{dn}{dt} = -\frac{n}{\tau_L} \quad (1)$$

where n is the density of the plasma and τ_L the plasma decay time. In a complex plasma, plasma losses are due to the diffusion of the ions and the electrons toward the wall of the reactor and by recombination onto the dust particle surfaces. Consequently, the plasma decay time τ_L is:

$$\tau_L^{-1} = \tau_D^{-1} + \tau_Q^{-1} \quad (2)$$

where τ_D is the plasma diffusion time and τ_Q the dust particle absorption time. As the dust particles are charged due to the fluxes of ions and electrons flowing to their surfaces, the dust particle absorption time will depend on the charge (and surface potential) of the dust particle. Using the orbital motion limited approach the charge on a dust particle is given by [2]:

$$\frac{dZ_d}{dt} = J_e - J_i = \pi r_d^2 [n_e v_{Te} e^{-\varphi} - n_i v_{Ti} (1 + \frac{T_e}{T_i} \varphi)] \quad (3)$$

where Z_d is the dust particle charge number, $J_{i(e)}$ is the ion (electron) flux, r_d is the dust particle radius, $n_{i(e)}$ is the ion (electron) density, $v_{Ti(e)}$ is the ion (electron) thermal speed, $T_{i(e)}$ is the ion (electron) temperature and φ is the dimensionless dust surface potential. The latter can be linked to the dust charge number Z_d by:

$$\varphi = \frac{Z_d e^2}{4\pi\epsilon_0 r_d k_B T_e} \quad (4)$$

where ϵ_0 is the vacuum dielectric permittivity and k_B is the Boltzmann constant. It could be noted that the influence of trapped ions on the dust particle charge is neglected. It has been shown that when $T_i \ll T_e$ and $(r_d/\lambda_D)^2 \ll T_i/T_e$ where λ_D is the Debye length, the trapped ions play a significant role in the charging process of dust particles [15,16] and Eq.3 has to be modified appropriately. However, for the conditions we are interested in, $(r_d/\lambda_D)^2 \sim T_i/T_e$.

In a complex plasma afterglow, recombination on dust particle surfaces is directly linked to the flux of ion onto the dust particles as the dust particles are negatively charged in a laboratory plasma ($Q_d = -Z_d e$ where Q_d is the dust particle charge and e is the elementary charge). Consequently, the dust particle absorption time τ_Q can be written as :

$$\tau_Q^{-1} = \pi r_d^2 n_d v_{Ti} (1 + \frac{T_e}{T_i} \varphi) \quad (5)$$

In a dust-free plasma ($n_e = n_i$), the equilibrium surface potential of an isolated dust particle can be found by solving $dZ_d/dt = 0$ and thus by solving:

$$\left(\frac{T_i}{T_e} \frac{m_e}{m_i}\right)^{1/2} (1 + \frac{T_e}{T_i} \varphi_0) \exp(\varphi_0) = 1 \quad (6)$$

In a complex plasma, however, the ion density n_i and the electron density n_e are different due to the charging of the dust particles. However, as the plasma is quasi-neutral, the

electron density can be deduced using the neutrality equation:

$$n_e = n_i - Z_d \cdot n_d \quad (7)$$

The ratio of the electron density to the ion density can be thus written as:

$$\frac{n_e}{n_i} = 1 - \frac{Z_d n_d}{n_i} = 1 - P_H \quad (8)$$

where $P_H = Z_d n_d / n_i$ is the Havnes parameter. As it can be seen from Eq.7 and Eq.8, for very low dust density, the electron density is very close to the ion density ($n_e \simeq n_i$ and $P_H \sim 0$). Consequently, the surface potential of the dust particle will be the same as for an isolated dust particle and the dust particle absorption time τ_{Q_0} is inversely proportional to the dust density:

$$\tau_{Q_0}^{-1} = \pi r_d^2 n_d v_{Ti} (1 + \frac{T_e}{T_i} \varphi_0) \quad (9)$$

When the dust density increases, however, the electron and ion densities start to deviate from each other and the Havnes parameter increase. Consequently, solving $dZ_d/dt = 0$, the dust surface potential follows:

$$\left(\frac{T_i}{T_e} \frac{m_e}{m_i}\right)^{1/2} (1 + \frac{T_e}{T_i} \varphi) \exp(\varphi) = 1 - P_H \quad (10)$$

This equation has to be solved numerically and the value of the surface potential explicitly depends on the dust particle density. This will directly affect the dust particle absorption time. However, if the dust density is not too high, the deviation of the dimensionless dust surface potential from the isolated dust particle surface potential will be small so one can write $\varphi = \varphi_0 + \Delta\varphi$. Using a first order approximation, Eq.10 can be rewritten as:

$$\begin{aligned} \left(\frac{T_i}{T_e} \frac{m_e}{m_i}\right)^{1/2} \left(1 + \frac{T_e}{T_i} (\varphi_0 + \Delta\varphi)\right) \exp(\varphi_0) (1 + \Delta\varphi) \\ = 1 - \frac{Z_d n_d}{n_i} \end{aligned} \quad (11)$$

From Eq.6 and Eq.4, it can then be deduced that:

$$\begin{aligned} \Delta\varphi = - \left(1 + \left(\frac{T_e}{T_i} \frac{m_e}{m_i}\right)^{1/2} \exp(\varphi_0) + \frac{4\pi\epsilon_0 r_d k_B T_e n_d}{e^2 n_i}\right)^{-1} \\ \times \frac{4\pi\epsilon_0 r_d k_B T_e}{e^2} \frac{\varphi_0 n_d}{n_i} \end{aligned} \quad (12)$$

In typical laboratory plasma, $(T_e m_e / T_i m_i)^{1/2} \exp(\varphi_0) \sim 10^{-2}$ and $(4\pi\epsilon_0 r_d k_B T_e n_d) / (e^2 n_i) \sim 10^{-1}$, thus:

$$\Delta\varphi \simeq - \frac{4\pi\epsilon_0 r_d k_B T_e}{e^2} \frac{\varphi_0 n_d}{n_i} \sim -Z_{d0} \frac{n_d}{n_i} \quad (13)$$

where Z_{d0} is the charge of an isolated dust particle. The dust particle absorption time can be rewritten as:

$$\begin{aligned} \tau_Q^{-1} \simeq \pi r_d^2 n_d v_{Ti} \left(1 + \frac{T_e}{T_i} \varphi_0\right) \\ - \pi r_d^2 n_d^2 v_{Ti} \cdot \frac{T_e}{T_i} \frac{4\pi\epsilon_0 r_d k_B T_e}{e^2} \frac{\varphi_0}{n_i} \end{aligned} \quad (14)$$

The dust particle absorption time is no longer inversely proportional to the dust density. There is a term in n_d^{-2} which tends to attenuate the effect of the dust particles on plasma losses. Indeed when the dust density is high the dust surface potential is lower as is the dust charge number Z_d . Consequently the ion flux is reduced and the dust particle absorption time is increased compared to the value it would have if the dust particles can be considered as isolated.

3. Numerical results

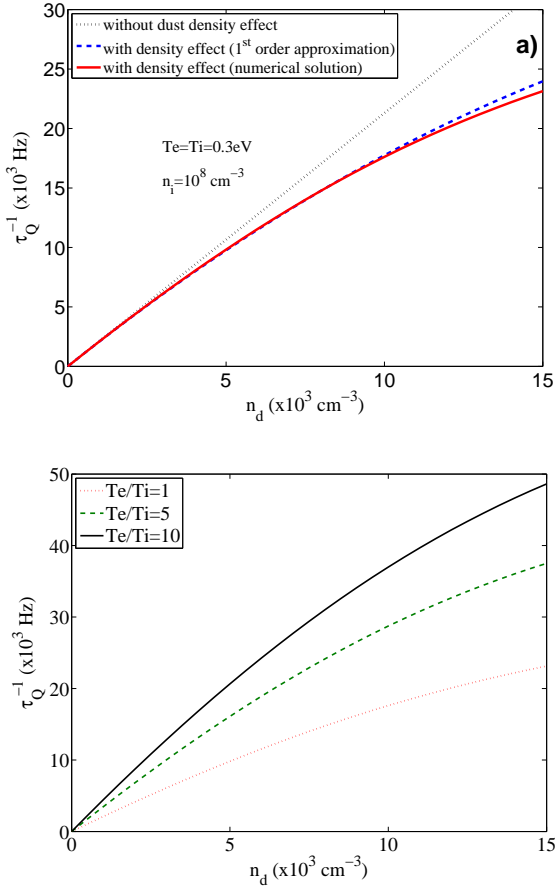


Fig. 1. (Color Online) Particle absorption frequency as a function of the dust density. a) With or without taking into account the dust density effect. b) Numerical solution for different T_e/T_i

In this section, exact numerical solutions of Eq.5 and Eq.10 are presented and compared to the approximate solution of Eq.14.

In Fig.1, the absorption frequency τ_Q^{-1} has been calculated for $n_i = 10^8$ cm $^{-3}$, $T_e = 0.3$ eV (close to experimental values of Ref.[14]) and a dust particle radius of $r_d = 10$ μ m. As it can be seen in Fig.1(a), for low dust densities the dust absorption frequency τ_Q^{-1} is increasing linearly as expected. On the contrary, for high dust density the absorption time τ_Q^{-1} deviates from linearity. The exact solution and the first order approximation are in agreement even though some small discrepancies are observed at high dust

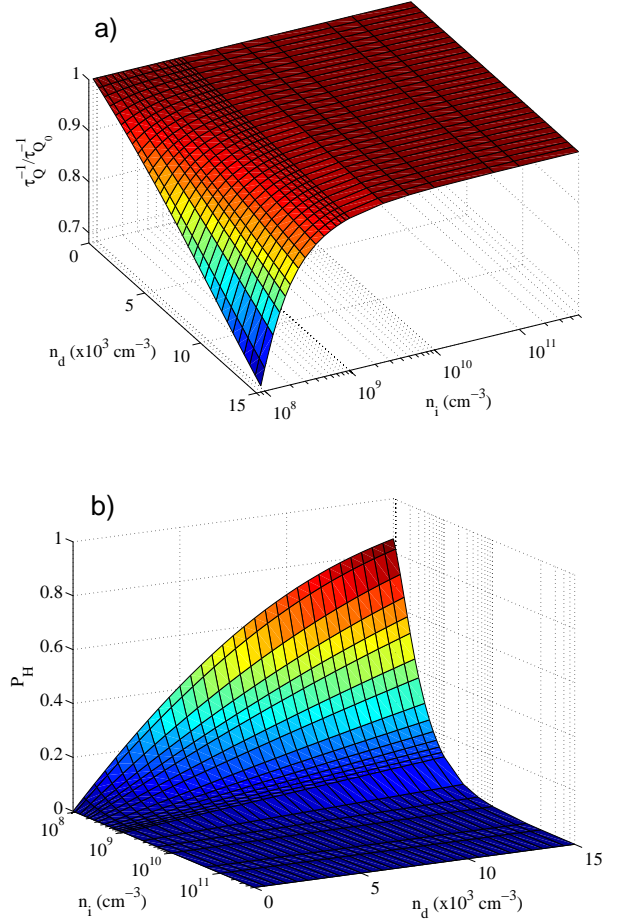


Fig. 2. (Color Online) a) Ratio of the dust particle absorption frequency taking into account dust density effect τ_Q^{-1} over the dust particle absorption frequency not taking into account dust density effect $\tau_{Q_0}^{-1}$ for different dust density and plasma density. b) Havnes parameter P_H for different dust density and plasma density.

density. In Fig.1(b), the exact solution is presented for different ratio T_e/T_i . As can be seen, the absorption frequency τ_Q^{-1} increases with increasing T_e/T_i . Indeed, when the electron temperature is higher than the ion temperature, ion and electron fluxes are greater at equilibrium (Eq.3) resulting in an increased dust particle absorption frequency. In Ref.[12], it is thus shown that the electron temperature relaxation in the plasma afterglow of a RF discharge results in a strong decrease of the dust particle charges.

In Fig.2, the ratio $\tau_Q^{-1}/\tau_{Q_0}^{-1}$ as well as the Havnes parameter P_H have been calculated for different dust densities and ion densities. As can be seen in Fig.2(a), the deviation from $\tau_{Q_0}^{-1}$ is marked at high dust density and low ion density. In Fig.2(b) these conditions correspond to a Havnes parameter close to 1. For small Havnes parameters (i.e. small dust density and high ion density), it can be seen that $\tau_Q^{-1}/\tau_{Q_0}^{-1} \sim 1$. This confirms that when dust particles can be considered as isolated inside the plasma the absorption frequency is directly proportional to the dust density while for high dust density the charge carried by a dust particle is reduced as the dust density increases and consequently

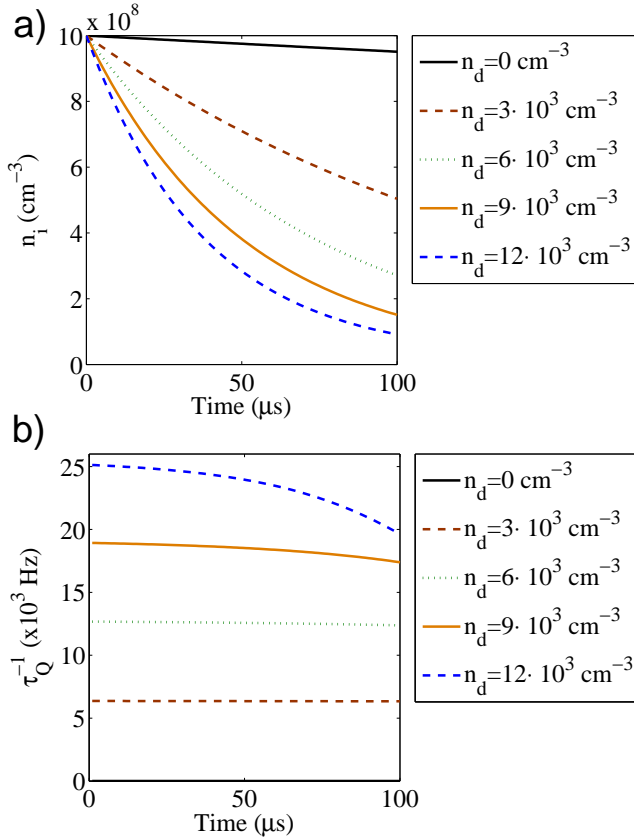


Fig. 3. (Color Online) Top: evolution of ion density n_i during the first microseconds of a plasma afterglow for different dust density. Bottom: Evolution of the dust particle absorption frequency τ_Q^{-1} during the first microseconds of a plasma afterglow for different dust density. The plasma diffusion frequency is $\tau_D^{-1} = 500 \text{ Hz}$ and $T_e = T_i = 0.3 \text{ eV}$

the dust absorption frequency does not evolve linearly with the dust density.

In a plasma afterglow, the plasma density decreases with time. Consequently the effect of the dust particles can become more and more important with time. In order to see this effect, the first moment of the decay of a complex plasma has been investigated using Eq.1, Eq.2, Eq.5 and Eq.8. The results are presented in Fig.3. The plasma diffusion loss is taken into account by choosing a plasma diffusion frequency $\tau_D^{-1} = 500 \text{ Hz}$ (which is a typical value for a laboratory discharge with an argon pressure around 1 Torr and these plasma parameters). As can be seen in Fig.3(a), the dust particles enhance plasma losses and the larger the dust density, the larger the effect on plasma losses. In Fig.3(b), it can be seen that at the very beginning of the plasma afterglow, the absorption frequency is roughly proportional to the dust density. This is due to the high value of the plasma density at this time which allows a small Havnes parameter and thus dust particles can be considered as isolated. However, as the density decreases, the effect of the dust particles become more and more important and the particle absorption frequency decreases. Indeed the Havnes parameter increases with time as the plasma den-

sity decreases. Consequently the dust particle charging is more and more affected by the presence of the other dust particles. The ion flux as well as the dust particle charge number decrease leading to a decrease of the dust absorption frequency. This effect is perfectly visible in Fig.3(b) for high dust density.

4. Discussion and Conclusion

As we demonstrated in Sec.3, the dust density influences greatly the dust absorption-recombination process in an afterglow plasma. Thus, the dust absorption frequency does not increase linearly with the density, and for high density it is smaller than the absorption frequency that would occur if each dust particle could be considered as isolated in the plasma. Moreover, it was shown in Sec.2 and Sec.3 that if the dust density is not too high, a first order approximation of the absorption frequency matches very well with the exact solution. In Eq.14, there are only a few parameters to know (T_e , T_i , r_d , φ_0 and n_i). Consequently, it is possible to use the measurement of the absorption frequency in the afterglow of a complex plasma in parallel with other diagnostics to deduce some important parameters of the plasma.

For example, in Ref.[14], the dust particle absorption frequency has been measured in the afterglow of a linear pulsed discharge. The argon pressure was 1.9 Torr and the density of dust varied from 0 to 10^4 cm^{-3} . The dust particles had a mean radius $r_d \simeq 15 \mu\text{m}$. It is reported that the electron temperature was roughly equal to the ion temperature ($T_e \sim T_i$) [14]. Consequently, the influence of trapped ions on the dust particle charge can be neglected. In Fig.4, experimental results from Ref.[14] are fitted using Eq.9 and Eq.14. The fit gives $T_i \simeq 0.042 \text{ eV}$, $(T_e/T_i)\varphi_0 = 4.4$ and thus assuming $T_i \leq T_e \leq 5T_i$ (depending when the measurement have been performed in the plasma afterglow), it gives $10^7 \text{ cm}^{-3} \leq n_i \leq 5 \cdot 10^7 \text{ cm}^{-3}$. The range for the ion density and the ion temperature are much lower than those that were supposed in Ref.[14] but it could be due to the fact that their measurements were performed quite late in the plasma afterglow and temperature relaxation needed to be taken into account.

To conclude, the influence of the dust density on plasma losses has been studied. It has been shown that the presence of dust particles can drastically shorten the plasma loss time and that the increase of the dust absorption frequency does not depend linearly on the dust particle density. Finally, by comparing our results with existing experimental data, the possible use of absorption frequency measurement as a diagnostic for complex plasma is mentioned. Comparison with existing experimental data [14] supports this idea.

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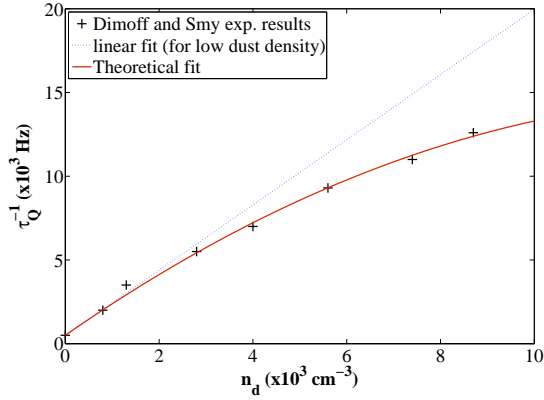


Fig. 4. (Color Online) Fit of experimental results of Ref.[14] using the first order approximation (Eq.14)

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