# Observation of the Effects of Dust Particles on Plasma Fluctuation Spectra

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Charged dust particles are theoretically expected to modify the amplitude and spectrum of plasma fluctuations, and this can eventually provide novel diagnostic tools. Direct experimental evidence of the effects of dust particles on the fluctuations of a low collisionality plasma is reported, in agreement with the expectations of kinetic theory.

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The presence of charged dust particles in a plasma can change its basic properties, due essentially to the dissipative effect of the charging collisions of plasma particles on dust, which produce fluctuations of the dust charge and collected fluxes. Charged dust particles can change the amplitude and spectrum of the plasma fluctuations [1,2]. These are due to particle discreteness, are directly related to dissipation in the system [3,4], and are always present in any system of particles, even at equilibrium, unlike perturbations, waves, and instabilities. The effects of dust on the latter have been known for a long time (see recent reviews [5,6]), while observations of the effects on plasma fluctuations have not yet been reported.

Such experimental tests would be a crucial benchmark of fundamental theoretical concepts of plasma fluctuations and can also provide new diagnostics for dust in plasmas, as the effects depend on dust size, density, and charge. To be measurable, these require a very quiescent plasma: the presence of waves and instabilities would mask the low level fluctuations driven by natural particle fluctuations (discreteness). Here we present observations of dust effects on plasma fluctuations in support of the theory. The measurements were carried out in a cusp configuration where the plasma is held in stable equilibrium [7].

The plasma fluctuations induced by the discreteness of the dust particles have low frequencies $\omega \simeq k v_{\rm Td}$, where $v_{\rm Td}$ is the mean dust velocity (the thermal velocity for thermal distributions of dust particles) [1,8,9], as compared to the fluctuations induced by the discreteness of the plasma particles. In this experiment the frequencies are much larger than $k v_{\rm Td}$, for the wave numbers considered, so that dust-induced fluctuations can be neglected and the theory of fluctuations induced by the plasma particle discreteness reported in Ref. [2] is used. This theory has been developed taking into account not only the fluctuations of the dust charge [10] but include the contribution from the fluctuations of the collected fluxes and the dissipation due to the charging collisions.

The experiment has been performed in a cusp plasma device at the Institute of Plasma Physics in Milan (for details, see Ref. [11]). The cusp magnetic field configuration is obtained by two identical bundles of coaxial solenoids where each bundle carries the same electric current intensity but with opposite directions. The static magnetic field has an intensity of 0.26 T at the point cusp and 0.156 T at the line cusp. The plasma source is located at one point of the cusp and is fed with gas (Ar or a mixture of Ar-$CH_4$) through a mass flow controller that maintains a discharge pressure between $7 \times 10^{-2}$ and $2 \times 10^{-2}$ Pa under a flow rate spanning from 6 to 3 $\mathrm{cm}^3/\mathrm{min}$ (referred to 0 °C and 1 bar). The plasma source is a microwave generator at the frequency of 2.45 GHz powered at 500 W. The microwaves are launched to the center of the cusp device by a rectangular waveguide, located along the point cusp, carrying the $TE_{1,0}$ mode. For the conditions investigated the ion density is $n_i \sim 10^{11}\ \mathrm{cm}^{-3}$ and the electron temperature is $T_e \sim 3$ eV.

For the pressure range studied, the ion mean free path is 2–8 cm and the electron mean free path is 1–4 m. The ion $R_{\rm Li}$ and electron $R_{\rm Le}$ Larmor radii are changing from infinity at the center to 1 cm and 0.04 cm, respectively, at 1 cm distance from the center. Hence, the central region of the discharge is a *collisionless* plasma with essentially *unmagnetized* ions and weakly magnetized electrons. The probe measurements revealed flat (less than 15% variations) density profiles up to a distance of 2 cm from the center.

The experiment was performed in discharges in an Ar-$CH_4$ mixture, which decomposes mainly into $Ar^+$, $H_x^+$, hydrocarbon ions and condensed carbon black particles (dust) [12,13], of different shapes and with a size distribution, similar to the case of space and fusion scrape-off layer plasmas. Though operated at gas pressures lower than typically reported in the literature, the cusp configuration with its high plasma density allows efficient dissociation of methane and formation of particles (likely of nanometer size), as has been reported for the present experimental apparatus in Refs. [11,14]. For the experiment reported here the production of carbon dust was confirmed by Raman analysis of the ceramic probe holder used in the campaign.

We found that discharges in pure Ar and Ar-$CH_4$ mixture are similar to each other macroscopically (similar density profiles). That means that the only difference between these discharges is the production of the carbon particles in the latter and indicates that the number density of the dust produced was modest. This allows a comparison between the plasma fluctuations spectra in pure Ar and in Ar-$CH_4$ mixture plasmas. Notice that in the setup used it is not feasible to eliminate nanometer dust particles completely so we might expect some residual dust always present in the machine.

Averaged plasma parameters and the density fluctuations are measured by a cylindrical molybdenum probe of 4.7 mm length and 0.075 mm radius, located at the center of the device. Since $R_{\mathrm{Li},e} \rightarrow \infty$ at the probe position, the probe can be considered to be in the unmagnetized, collisionless regime [15] for the conditions studied. In this regime the ion saturation current is proportional to $n_i\sqrt{T_e}$ and the *spectral* characteristics of its fluctuations basically reflect those of the density fluctuations. We note that if accurate *phase* measurements are desired, this might not hold true anymore [15].

*Experimental results.*—The measurements in the center of Ar discharges showed that the plasma in the conditions investigated is quiescent, with fluctuation level below 2%, and revealed power spectra decaying with frequency, as shown in Fig. 1(a) (lower curve). Though spectra of such shape might be caused by turbulence, this is excluded due to the low fluctuation level. Measurements along the cusp radius also have revealed that the spectra are identical within the central region of the discharge. Taking into account that flat profiles are unlikely to give rise to gradient driven instabilities, the experimental evidence allows the interpretation of the measurements as plasma fluctuations.

Addition of 25% of $CH_4$ results in the modifications of the spectra [Fig. 1(a), middle curve], namely, increase of the power at very low frequencies and appearance of a peak at higher frequencies. With increased percentage of methane (up to 50%) the modifications become more pronounced [Fig. 1(a), upper curve].

To verify that the observed features are due to the carbon dust particles formed in the Ar-$CH_4$ discharge and not to different plasma composition, experiments in Ar-$NH_3$ mixtures have been performed. The choice of $NH_3$ has been motivated by the fact that it decomposes into ions of similar mass [16] and has similar cross section and close ionization potential. The spectra measured in 50%–50% Ar-$NH_3$ discharge reproduced that of pure Ar and did not exhibit any features of the spectra found in Ar-$CH_4$ mixtures. This is to be expected as different ion mass can shift the frequency of the ion-acoustic mode, but there is no physical mechanism to produce an increase in fluctuation power.

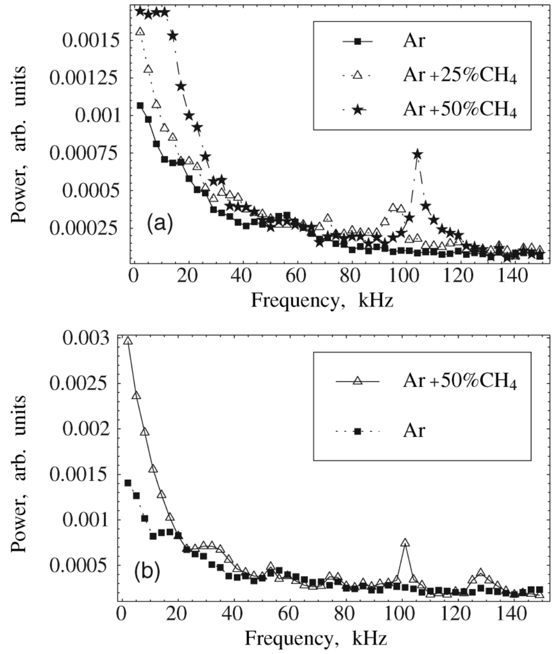


FIG. 1. Power spectra of ion density fluctuations in different gas mixtures for two different runs, (a) and (b).

The spectra obtained are not very sensitive to the flux rate (pressure) and the ion background density, and, in the parameter range investigated, we observe the same effects within statistical variations [Fig. 1(b)].

Results presented in Figs. 1(a) and 1(b) show that, with the exception of the peak(s), the fluctuation power at higher frequencies is the same for all the discharges investigated. This indicates that the plasma conditions in these discharges are almost identical and the comparison of the spectra is indeed meaningful.

*Main predictions of the kinetic model.*—In Ref. [2] the theory was developed for unmagnetized plasmas, neglecting collisions of all species with neutrals, taking into account the dissipation due to the plasma particles-dust collisions, the fluctuations of the dust charge $q$ around the equilibrium value $q_{\mathrm{eq}} = -eZ_d$, and the fluctuations of the collected plasma fluxes. To first order in the parameter $\epsilon = (n_d\lambda_{\mathrm{Di}}^3)(a/\lambda_{\mathrm{Di}})^2$ (where $a$ and $n_d$ are the dust grain radius and dust number density, and $\lambda_{\mathrm{Di}}$ the ion Debye length), the spectral density of the plasma density fluctuations for each species $\alpha = e, i$ is found to be $S^{\alpha}_{\mathbf{k},\omega} = S^{\alpha(P)}_{\mathbf{k},\omega} + \Delta S^{\alpha}_{\mathbf{k},\omega}$, where

$$S^{\alpha(P)}_{\mathbf{k},\omega} = S^{\alpha(0)}_{\mathbf{k},\omega}\left(1 - 2\,\mathrm{Re}\left\{\frac{\chi^{\alpha}_{\mathbf{k},\omega}}{\varepsilon_{\mathbf{k},\omega}}\right\}\right) + \frac{|\chi^{\alpha}_{\mathbf{k},\omega}|^2}{|\varepsilon_{\mathbf{k},\omega}|^2}(S^{i(0)}_{\mathbf{k},\omega} + S^{e(0)}_{\mathbf{k},\omega}),$$

$$\Delta S^{\alpha}_{\mathbf{k},\omega} = \frac{2\nu}{\omega^2 + \nu^2}\frac{|\chi^{\alpha}_{\mathbf{k},\omega}|^2}{|\varepsilon_{\mathbf{k},\omega}|^2}\sum_{\beta} T^{\beta}_{\mathbf{k},\omega} + 2\,\mathrm{Im}\left\{\frac{\chi^{\alpha}_{\mathbf{k},\omega}}{(\omega + i\nu)\varepsilon_{\mathbf{k},\omega}}\right\}T^{\alpha}_{\mathbf{k},\omega}.$$

Here $\chi^{\alpha}_{\mathbf{k},\omega}$ and $\varepsilon_{\mathbf{k},\omega}$ are the ion (electron) susceptibilities and permittivity of the dusty plasma, including the effect of dissipation due to collisions with dust, and

$$T^{\beta}_{\mathbf{k},\omega} = \frac{1}{(2\pi)3} \int \nu_{d,\beta}(v)\Phi^{\beta}(\mathbf{v})\delta(\omega - \mathbf{k}\cdot\mathbf{v})d\mathbf{v},$$

where $\Phi^{\alpha}(\mathbf{v})$ are the distribution functions.

The capture frequency of plasma particles in collisions with dust is $\nu_{d,\alpha}(v) = n_d v \sigma_{\alpha}(q, v)$ and the charging frequency is given by

$$\nu = -\sum_{\alpha} e_{\alpha} \int v\sigma'_{\alpha}(q_{eq}, v)\Phi^{\alpha}(\mathbf{v})d\mathbf{v},$$

where $\sigma_{\alpha}$ is the cross section for capture by a grain of charge $q$, the prime denotes derivative with respect to charge, and the relative velocity is assumed to coincide with the ion (electron) velocity.

The spectral density of the natural plasma density fluctuations is given by

$$S^{\alpha(0)}_{\mathbf{k},\omega} = \langle \delta n^{\alpha(0)}_{\mathbf{k},\omega} \delta n^{\alpha(0)*}_{\mathbf{k},\omega} \rangle = \frac{1}{(2\pi)3} \int \Phi^{\alpha}(\mathbf{v})\delta(\omega - \mathbf{k}\cdot\mathbf{v})d\mathbf{v}.$$

The second term in the expression for $S^{\alpha}_{\mathbf{k},\omega}$ is only due to the effect of dust. The effect of dust in the first term is in the modified responses and in the correlator of the natural fluctuations, since the presence of dust generally changes the plasma particles equilibrium distribution functions [17]. With no dust the first term reduces to the usual expressions for plasma fluctuations [3,4].

For a qualitative comparison with the experimental results, Maxwellian distributions are used in the numerical calculations, with a temperature ratio $\tau \equiv T_i/T_e \simeq 10^{-2}$, and orbit motion limited cross sections [5,6]. The results for the spectral density of ion density fluctuations $S^{i}_{\mathbf{k},\omega}$ are shown in Fig. 2 where $S^{i}_{\mathbf{k},\omega}$ is plotted versus $k$ (in units of $\lambda_{\mathrm{Di}}$) for two values of the frequency and of the dust density parameter $P = n_d Z_d / n_i$.

The range of wave numbers depends on the limitations imposed by the experimental setup, the size of the device $L$ and of the probe $l$ determine $k_{\min} = 2\pi L^{-1}$ and $k_{\max} = 2\pi l^{-1}$, respectively, but there is no clear rule for the choice of $L$, $l$. The numerical calculations have been done with the choice $L \simeq 2.6$ cm (approximately the size of central region of device), $l \simeq 0.015$ cm (approximately the probe diameter). The results are not very sensitive to the value of $L$ ($k_{\min}$); the value of $l$ ($k_{\max}$) does not change the shape of the resulting spectra, but has an effect on the absolute value of the power. This should be carefully taken into account for quantitative comparisons with measurements.

The peaks, present for the larger value of frequency, correspond to the ion-acoustic mode $\omega = kV_s$ modified by the presence of dust, $V_s = V_{s0}(1-P)^{-1/2}$, where $V_{s0} = (T_e/m_i)^{1/2}$ is the ion-acoustic velocity. For the chosen value of the grain radius, $a = 8$ nm, the curves

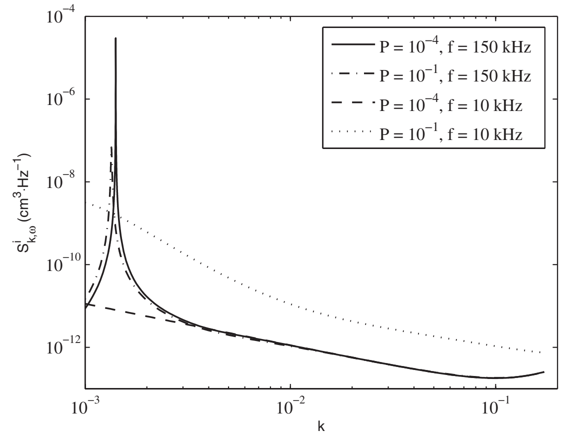


FIG. 2. Spectral density of ion density fluctuations versus wave number $k$ normalized to the ion Debye length for two values of the frequency and density parameter $P$. The grain radius is $a = 8$ nm.

for $P = 10^{-4}$ do not differ from the case with no dust, and the curves for $P = 10^{-1}$ show therefore the effects of dust on the spectral density of ion fluctuations. The ion-acoustic mode is present for frequencies $f \geq 106$ kHz in this range of wave numbers; it appears for $k < k_{\min}$ for lower frequencies. In the presence of dust the corresponding peak is shifted to smaller $k$ (increase in phase velocity) and decreases in amplitude (2 orders of magnitude in the example in Fig. 2), due to the larger dissipation from charging collisions with respect to Landau damping in the imaginary part of the permittivity. At low frequency, where the ion-acoustic modes are not present, the curves differ by 1 or 2 orders of magnitude in the whole range of $k$. These features are essential to understand the following comparison with the experimental curves.

For a comparison with the experiment, the single point correlations are needed, that is the integral of $S^{i}_{\mathbf{k},\omega}$ over $k$. The $k$ integral has been performed in the chosen range of wave numbers $k$. The power spectral density (PSD) of the single point correlations for the case without dust is flat up to the frequency of 106 kHz and then grows due to the large contribution of the ion-acoustic modes, as shown by the curve for $P = 10^{-4}$ in Fig. 3. This is a result of the upper limit of $k$ integration, the "jump" disappears if the integral is extended to all $k$. In the presence of dust the behavior of the integrated curve is very sensitive to the values of $a$ and $P$. From the numerical analysis the following conclusions were reached: (i) The contribution from the modes becomes smaller and eventually negligible with increasing dust density, in accordance with the decrease in amplitude shown in Fig. 2. The jump at 106 kHz can still be seen at $P \simeq 10^{-2}$ but is no longer present for the higher values of $P$ in Fig. 3. (ii) For $a \leq 1$ nm the increase in power at the lower frequencies tends to disappear and for $a > 10$ nm the curves at different $P$ do not converge at high frequencies.

Comparing with the experimental curves in Fig. 1 this implies that the measured spectra are consistent with the

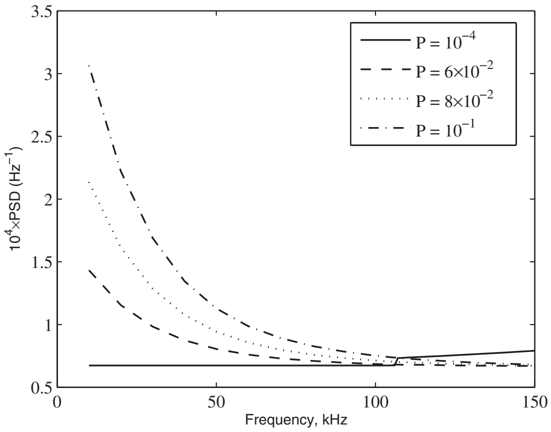


FIG. 3. The integrated spectral density of ion density fluctuations for four values of the density parameter $P$. For the smallest value the curve coincides with the case of no dust present. The grain radius is $a = 8$ nm.

effects of particles with size of a few ($\leq 10$) nanometers and with number density $n_d \simeq 10^8$ cm$^{-3}$ corresponding to $P > 10^{-2}$ (for $Z_d$ estimated from the orbit motion limited model).

As discussed above, nanometer particles are likely to form in the discharge used and hence the selection of the particle size by the model agrees with the experiment. The high dust density required is likely due to the presence of residual dust in the machine, which is consistent with the fact that flat power spectra (case of no dust in Fig. 3) have never been observed.

As seen from the equations, the effects of dust on the spectral density are quite different for frequencies lower or larger than the charging frequency $\nu$. This scales as $an_i/\sqrt{T_i}$ and, for $a = 8$ nm and the plasma parameters in the experiment, it has a value of 28 kHz. Analytic expansions of the theoretical expressions lead to the asymptotic behavior for the spectral density $\propto \epsilon/\nu$ for $\omega \ll \nu$ and $\propto \epsilon/\omega$ for $\omega \gg \nu$, so that the low frequency part of the spectrum is enhanced as $P \sim n_d/n_i$ is increased and the high frequency tail goes as $1/\omega$.

The presence of peaks in the experimental curves at certain frequencies (see Fig. 1) is not explained by the present fluctuation theory. It can be due to different reasons. There could be resonances due to physical boundaries in the machine. However, since the peaks are observed only in Ar-$CH_4$ mixture, we do not consider this as a convincing explanation. Also, the use of Maxwellian distributions, in particular, in the calculation of the correlator of the natural fluctuations, where any effect of dissipation other than Landau damping is absent, is a limit on the numerical results of the model. Inclusion of dissipation in the correlator requires the full solution of the kinetic equation for the regular plasma distributions and is beyond the scope of this Letter. Another possibility could be that the presence of dust grains with different sizes, which is the case for the experiment, could modify both the dispersion and the dissipative properties of plasma fluctuations (see, for example, the study of slow MHD waves in finely structured plasmas in Ref. [18]). We leave the interpretation of the resonant-like frequency peaks to a future study.

In conclusion, the first observations of the effects of dust particles on plasma fluctuations support the theoretical predictions based on the self-consistent theory including the charging processes of the dust particles. New systematic experiments with fully controlled dust parameters can allow more quantitative comparisons with the theoretical model and open possible roads to the development of diagnostic tools for dust based on fluctuation measurements, particularly useful for invisible (nanometer) dust particles.

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