

Transverse ionization instability of the elongated dust cloud in the gas discharge uniform positive column under microgravity conditions

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Abstract. A new kind of dusty plasma instability was observed in the joint Russian-European “Plasma Kristall-4” space experiment on board of the International Space Station. An elongated cylindrical dust particle cloud of 0.9 cm diameter with a length of 20 cm was formed in the uniform positive column of a dc discharge operating in a polarity switching mode (dc/ps-mode). The discharge was operated in a glass tube of 3 cm inner diameter with a total length of 85 cm filled by argon at a pressure of 0.5 mbar. The dc/ps discharge was operated at 1 mA with a polarity switching frequency of 500 Hz. During the experiment, all the dust particles vibrated synchronized in the same phase in the direction perpendicular to the tube axis with a frequency of 24 Hz and peak-to-peak amplitude of 0.2 mm. The vibration was attended by discharge glow fluctuation. The nature of the cloud vibration is discussed.

Dust particles immersed into discharge plasma obtain electric charge due to electron and ion fluxes and form strongly coupled systems. The presence of dust particles in plasma modifies already known plasma instabilities, for example, ion-acoustic instability [1] into a dust-acoustic instability [2–5], and creates completely new plasma instabilities such as a dust “spoke” rotation [6] and “heatbeating” [7] in a capacitive rf discharge plasma. The remarkable features of the dust instabilities are extremely large characteristic times of a period of their development (up to several seconds) and small phase velocities of observed disturbances (about a few cm/s).

Recently, we observed instability of a new type in the dusty plasma formed in the low-current positive column under microgravity conditions. The experiment was performed during Commission session of the “Plasma Kristall-4” space experiment [8] on board of the International Space Station 1–7 June 2015. The discharge chamber was similar to that described in [9] for tests in parabolic flights. This was a glass tube of 3 cm inner diameter with a total length of 85 cm filled by argon at a pressure of 0.5 mbar. At the beginning of the experiment, the spherical monodisperse plastic dust particles with a diameter of $3.34\ \mu\text{m}$ ($\rho = 1.5\ \text{g/cm}^3$) were injected into the discharge plasma in vicinity of the cathode (left side of figure 1a) and started to drift



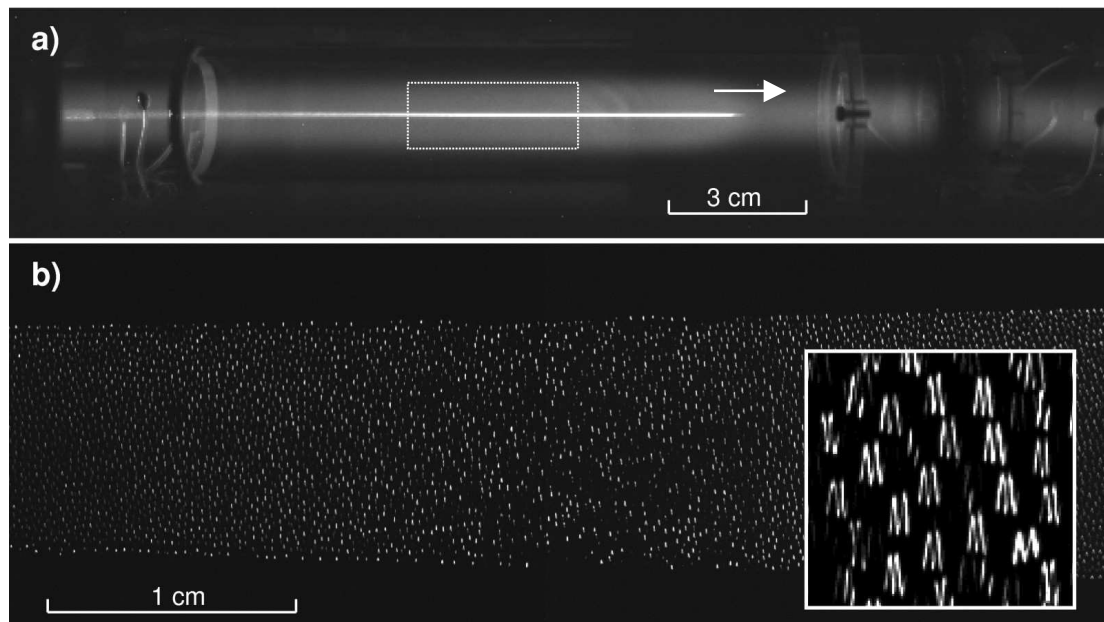


Figure 1. (a) General view of PK-4 discharge tube with elongated dust cloud obtained by PGO camera; bright line in the center is the cloud illuminated by laser sheet; dotted line rectangle in the center is FoV of 2 high resolution PO cameras; white arrow shows a direction of dust cloud transportation. (b) FoV of 2 high resolution cameras; insert in the right side is a superimposition of 3 consequent frames enlarged view of a part of the figure.

to the center of the tube. The dust particles were illuminated by a green laser “sheet” oriented perpendicular to the plane of figure 1a. A position of dust particle cloud was controlled using a low resolution side view video camera–plasma glow observation (PGO) camera (figure 1a). Additionally, the PK-4 setup is equipped by two high-resolution video particle observation (PO) cameras operated at 35 frames per second with a total field of view (FoV) of $44 \times 16 \text{ mm}^2$, which can be shifted along the tube. In the present experiment the FoV was tuned at the tube center as shown in figure 1a.

During the experiment, as soon as the dust particles had appeared in the FoV, a cosmonaut manually had changed the discharge mode from the dc to a symmetrical polarity switching dc mode (ps/dc mode) [10]. The dc/ps discharge was operated at 1 mA with a polarity switching frequency of 500 Hz. Due to averaging over time, net electrical force acting on a dust particle was equal to zero, and the dust cloud drift was stopped. The stopped dust cloud was uniform and stable with a total length of about 20 cm, a diameter of 0.8–1 cm, and a dust particles number density of $7 \times 10^4 \text{ cm}^{-3}$ with an accuracy of 30% (figure 1b). All of a sudden, all the dust particles started to oscillate synchronized in the same phase and in the same direction perpendicular to the tube axis with a frequency of 24 Hz and maximal peak-to-peak amplitude of 0.2–0.25 mm. The vibration was attended by discharge glow fluctuation. The trajectories of the grains during 3 consequent frames are presented in insert in figure 1b. A visible amplitude of the oscillations changed with time irregularly because of the direction of the vibration rotated around the tube axis. When the visible amplitude of the grain oscillation was small, fluctuations of the discharge glow nevertheless were observed by the PGO camera. But, a time resolution of the glow observation camera was not enough for analysis of these fluctuations. The frequency of oscillations was smaller than the time constant of the neutral gas friction for the grains ($\tau_{\text{nd}}^{-1} = 175 \text{ s}^{-1}$). So, the oscillations should be energized by some plasma processes.

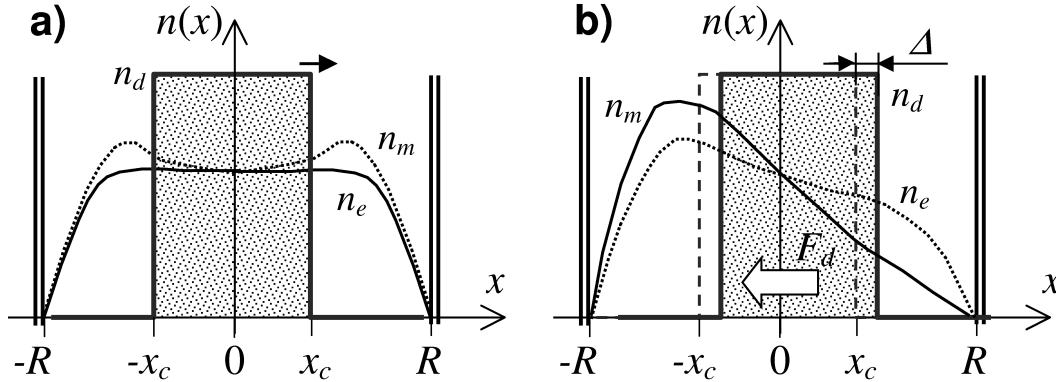


Figure 2. Scheme of simulated 1D flat discharge cell and distributions of plasma components: vertical double lines—flat camera walls; solid rectangle line—dust particle number density distribution $n_d(x)$; solid curve line—electron number density distribution $n_e(x)$; dotted curve line—metastable number density distribution $n_m(x)$. (a) Equilibrium symmetric position of dust layer; arrow is direction of a small position fluctuation of dust layer. (b) Dust layer has shifted on value Δ , discharge contracts in left channel; ambipolar electric field returns dust layer back to cell center.

A model of the discharge with the direct ionization can not explain such instability, because an ambipolar diffusion time is too small compare with the oscillation period. In such situation, an assumption that metastable atoms ionization dominates in the total ionization process, can explain the oscillation excitation.

Let us consider a simplified 1D model of the discharge in the flat geometry. A scheme of the model is presented in figure 2a. The dc discharge burns along two dielectric plates separated by a distance of $2R$. In equilibrium, a flat dust cloud with a width of $2x_c$ and a dust number density of n_d is placed symmetrically between the chamber walls. Inside the cloud, the electron density is a constant ($n_e = n_0$), as it is shown in figure 2a by the solid curve [11]. The electron balance in the discharge is given by the equation

$$\partial^2 n_e / \partial x^2 + \alpha n_m n_e - \beta n_d n_e = 0, \quad (1)$$

where n_e , n_m and n_d denote the number densities of electrons, metastable atoms and dust particles, correspondingly, α and β describe ionization and recombination processes, correspondingly. The equation for metastable atoms is

$$\partial n_m / \partial t = \gamma n_e - \tau^{-1} n_m, \quad (2)$$

where γ is the rate constant of the metastable states generation, τ is the life-time of the metastables. In the stationary conditions, the equations (1) and (2) give

$$\partial^2 n_e / \partial x^2 + \alpha \gamma \tau n_e^2 - \beta n_d n_e = 0. \quad (3)$$

The ionization and recombination inside the cloud should be in the balance, because even small ambipolar field can strongly disturb charged dust component. Hence, inside the cloud

$$\alpha \gamma \tau n_e = \beta n_d. \quad (4)$$

Outside the cloud the equation (3) is simplified into

$$\partial^2 n_e / \partial x^2 + \alpha \gamma \tau n_e^2 = 0. \quad (5)$$

A solution satisfying to the conditions $n_e(x_c) = n_0$, $n'_e(x_c) = 0$, $n_e(R) = 0$ exists only when $\alpha\gamma\tau n_0(R - x_c)^2 = B(1/3, 1/2)^2/6 \approx 2.95$ (see appendix). In this case

$$n_e = n_0 f\left(\frac{x - x_c}{R - x_c}\right), \quad (6)$$

where $f(z) \approx 1 - 1.47z^2 + 0.72z^4 - \dots$.

If the cloud is spontaneously shifted on a value of Δ to the right wall, as shown in figure 2b, then the discharge contracts through the left free discharge space. The contracted discharge creates an ambipolar diffusion field acting on the negative charging dust particle with a restoring force F_d , that leads to dust cloud oscillation.

Now we consider small harmonic perturbation n_1 of the electron density n_e . The equation for the perturbation is

$$\partial^2 n_1 / \partial x^2 + \frac{2.95 n_e n_1 \left(1 + (1 + i\omega\tau)^{-1}\right)}{(R - x_c)^2} - \beta \delta n_d n_1 = 0. \quad (7)$$

The ω is the oscillation cyclic frequency. Below we will assume that $\omega\tau \ll 1$ and

$$1 + 1/(1 + i\omega\tau) \approx 2 - i\omega\tau. \quad (8)$$

The perturbations of dust density δn_d are strong, but localized in the thin layers of the Δ thickness at the cloud boundaries. Inside the cloud the function $n_1(x)$ can be assumed as linear:

$$n_1 = n_1(x_c)x/x_c \quad (9)$$

Outside the cloud a solution of the equation 7 with boundary condition $n_1(R) = 0$ is

$$n_1 = n_1(x_c) \left(g\left(\frac{x - x_c}{R - x_c}\right) - 2.95i\omega\tau u\left(\frac{x - x_c}{R - x_c}\right) \right), \quad (10)$$

where the functions

$$g(z) = 2.95 f'(z) \int_z^1 \frac{dt}{f'(t)^2} \approx 1 + 1.48z - 2.95z^2 + \dots, \quad (11)$$

and

$$u(z) = -0.339 \left(g(z) \int_0^z g(t)f(t)f'(t)dt + f'(z) \int_z^1 g(t)^2 f(t)dt \right) \approx 0.63z - 0.75z^2 - \dots \quad (12)$$

and f' is the derivation of the function f defined in the equation (6), see appendix for details.

The $n_1(x)$ has a bend at the cloud boundary due to the recombination on the dusty particles, so

$$\frac{\partial n_1}{\partial x}(x_c + 0) - \frac{\partial n_1}{\partial x}(x_c - 0) = \beta n_d n_0 \Delta \approx 2.95 n_0 \Delta, \quad (13)$$

the last equality follows the equation (4). Equations (9)–(13) define the relative perturbation of the electron density at the cloud boundary via the shift of the cloud:

$$\frac{n_1(x_c)}{n_0} = \frac{-2.95\Delta}{(R - x_c)(R/x_c - 2.49 + 1.92i\omega\tau)}. \quad (14)$$

Equation (14) shows that the critical size of cloud $R/x_c = 2.49$ exists, when the perturbation comes to infinity at zero frequency. This situation corresponds to a loss of resistance of the symmetric configuration of plasma even at the fixed central position of the cloud. When a space filled by dust particles is enough large, the discharge should contract into one of two dust-free channels (see figure 2).

The ambipolar electric field in the cloud is proportional to the gradient of the electron density:

$$E = -n_1(x_c)/(n_0 x_c) \times k_B T_e / e, \quad (15)$$

where k_B is the Boltzmann constant, T_e is the electron temperature, e is the elementary charge. The motion of the cloud can be ascribed by simple equation:

$$\frac{\partial^2 \Delta}{\partial t^2} = -\frac{eEZ}{m_d} - \frac{\partial \Delta}{\partial t} \tau_{nd}^{-1}, \quad (16)$$

or

$$-\omega^2 \Delta = -\frac{eEZ}{m_d} - i\omega \Delta \tau_{nd}^{-1}, \quad (17)$$

when Δ oscillates harmonically. Z and m_d are the charge number and the mass of the dust particle, τ_{nd} is the deceleration time of the dust particle due to the gas friction. The equations (14), (15) and (17) define the oscillation frequency for the dust oscillations as a root of the equation:

$$\omega^2 \left(\frac{R}{x_c} - 2.49 + 1.92\tau\tau_{nd}^{-1} \right) + i\omega\tau_{nd}^{-1} \left(1.92\omega^2\tau\tau_{nd} - \frac{R}{x_c} + 2.49 \right) = \frac{2.95k_B T_e Z}{m_d x_c (R - x_c)}. \quad (18)$$

The condition of the oscillation self-excitation is very sensitive to the parameter $(R/x_c - 2.49)$. For description of the experimental observations ($\omega = 151 \text{ s}^{-1}$, $Z \sim 4000$, $T_e \sim 4 \text{ eV}$, $m_d = 3.1 \times 10^{-14} \text{ kg}$, $x_c = 0.45 \text{ cm}$) the parameter R/x_c should be near to 2.6, what corresponds to $R = 1.18 \text{ cm}$, and $\tau \sim 0.6 \text{ ms}$. The difference of R and real tube radius (1.5 cm) can be attributed to a geometric factor and a presence of significant wall sheath due to low electron density. The metastable life-time of 0.6 ms is an order smaller than the diffusion time, that justifies applicability of the equation (2).

In conclusion, a new kind of transverse dusty plasma instability was observed in the joint Russian-European “Plasma Kristall-4” space experiment on board of the International Space Station. The instability was observed in the uniform positive column of the low pressure dc discharge in argon and never has been observed in neon. A model based on the assumption that metastable atoms ionization dominates in the total ionization process was proposed to explain the observed dust cloud oscillation.

Acknowledgments

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Appendix

The equation (5) is reduced to

$$\partial^2 f / \partial z^2 + \kappa f^2 = 0, \quad (\text{A.1})$$

where $\kappa = \alpha\gamma\tau(R - x_c)^2$ and $f(0) = 1$, $f'(0) = 0$ by substitutions $z = (x - x_c)/(R - x_c)$ and $n_e(z) = n_0 f(z)$. The function f is determined implicitly by the expression

$$z = \left(\frac{3}{2\kappa}\right)^{1/2} \int_f^1 \frac{du}{(1 - u^3)^{1/2}}. \quad (\text{A.2})$$

The condition $f(1) = 0$ corresponds to the condition for κ as follows

$$1 = \left(\frac{3}{2\kappa}\right)^{1/2} \int_0^1 \frac{du}{(1 - u^3)^{1/2}} = B(1/3, 1/2) (6\kappa)^{-1/2}, \quad (\text{A.3})$$

where $B(u, v)$ is the beta-function, or $\kappa = B(1/3, 1/2)^2/6 \approx 2.949$.

The function

$$g(z) = -\kappa f'(z) \int_z^1 f'(t)^{-2} dt \quad (\text{A.4})$$

is a root of the equation

$$\partial^2 g / \partial z^2 + 2\kappa f g = 0, \quad (\text{A.5})$$

and satisfies the conditions $g(1) = 0$ and $g(0) = 1$. Another solution of the equation (A.5) is $f'(z)$, which satisfies the condition $f(0) = 0$. The integral

$$\int_z^1 f'(t)^{-2} dt$$

can be calculated using the relation $f' = f'(1)\sqrt{1 - f^3}$. So,

$$\begin{aligned} \int_z^1 f'(t)^{-2} dt &= \int_z^1 \frac{dt}{f'(1)^2 (1 - f(t)^3)} \\ &= \int_z^1 \left[\frac{1}{f'(1)^2 (1 - f(t)^3)} - \kappa^{-2} (t^{-2} + 2) \right] dt + \kappa^{-2} (z^{-1} + 1 - 2z). \end{aligned} \quad (\text{A.6})$$

The derivation of f at $z = 1$ is easily obtained from equation (A2)— $f'(1) = -B(1/3, 1/2)/3 \approx -1.402$. The equation (A6) was used for deriving the expansion of $g(z)$ for small z (equation (11)). A solution of the equation

$$\partial^2 y / \partial z^2 + 2\kappa f y + \epsilon f y = 0 \quad (\text{A.7})$$

with small constant ϵ can be written in the form $y = \text{Const} (g + \epsilon u)$. Substituting this expression in equation (A7) and neglecting the ϵ^2 order term, we have the equation for u :

$$\partial^2 u / \partial z^2 + 2\kappa f u = -f g \quad (\text{A.8})$$

The solution of the equation (A.8) satisfying the conditions $u(0) = u(1) = 0$ is the function defined by the equation (12).

References

- [1] Michelsen P, Pecseli H L and Rasmussen J J 1979 *Plasma Phys.* **21** 61
- [2] Merlino R L, Barkan A, Thompson C and D'Angelo N 1998 *Phys. Plasmas* **5** 1607
- [3] Molotkov V I, Nefedov A P, Torchinskii V M, Fortov V E and Khrapak A G 1999 *J. Exp. Theor. Phys.* **89** 477
- [4] Khrapak S, Samsonov D, Morfill G, Thomas H, Yaroshenko V, Rothermel H, Hagl T, Fortov V, Nefedov A, Molotkov V, Petrov O, Lipaev A, Ivanov A and Baturin Y 2003 *Phys. Plasmas* **10** 1
- [5] Fortov V E, Usachev A D, Zobnin A V, Molotkov V I and Petrov O F 2003 *Phys. Plasmas* **10** 1199
- [6] Samsonov D and Goree J 1999 *Phys. Rev. E* **59** 1047
- [7] Heidemann R J, Couedel L, Zhdanov S K *et al* 2011 *Phys. Plasmas* **18** 053701
- [8] Pustynnik M Y *et al* 2016 *Rev. Sci. Instr.* **87** 093505
- [9] Fortov V, Morfill G, Petrov O, Thoma M, Usachev A, Hoefner H, Zobnin A, Kretschmer M, Ratynskaia S, Fink M, Tarantik K, Gerasimov Yu and Esenkov V 2005 *Plasma Phys. Control. Fusion* **47** B537
- [10] Usachev A, Zobnin A, Petrov O, Fortov V, Thoma M H, Hoefner H, Fink M, Ivlev A and Morfill G 2014 *New. J. Phys.* **16** 053028
- [11] Usachev A, Zobnin A, Petrov O, Fortov V, Thoma M H, Pustynnik M, Fink M and Morfill G 2016 *Plasma Sources Sci. Technol.* **25** 035009