

# DUST PARTICLE LEVITATION IN A HOT CATHODE DISCHARGE AT LOW ARGON PRESSURE

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When dust grains are embedded in a partially or a fully ionized plasma, they gain from zero to several thousands electric charges depending on their size and on the plasma conditions. As a consequence, they can influence the collective properties of the plasmas perturbing the plasma dispersion properties [1] or the transport characteristics [2]. In some conditions, a surprising crystallization [3] or self-organization behavior of the dust grains can be observed.

We show that it is possible to observe dust levitation and self-organization in the sheath edge of a disc plate located in the center of a dc discharge operating at low argon pressure ( $P_{\text{ar}} \sim 0.8$  mTorr). The negative charge of the dust grains is determined experimentally by different methods: i) We measure the potential profile of the plate sheath and presheath for different negative bias. For each profile, we measure the levitation height of an isolated dust. The balance of the gravitation force and the electric force at this point gives the dust charge, ii) an initial impulsion exerted on a dust initiates a resonance oscillation (without damping) whose frequency depends on the charge.

We report, for the first time, the study of a collision between two dust grains. Using the classical Coulombian scattering relations and taking into account the measured parameters like scattering angles, impact parameter, minimum approach radius, we can find the dust grain charge too, in agreement with the charge found in i) and ii).

We observe a two-dimensional self-organization of the dust grains in centered hexagonal structures. This example of pattern is obtained at low argon pressure when the gas flux regime is considered as molecular. So, in such experimental conditions, the question of the dust grains cooling remains an open topic.

## 1. Experimental conditions

The argon plasma is produced by a dc discharge [4] between the grounded wall of a multipolar device and two heated negatively biased tungsten filaments. The discharge operates in the so-called “temperature-limited current” regime. A negatively biased disc plate, is set horizontally in the center of the chamber. Glass micro-balloons ( $110 \text{ kg/m}^3$  mass density, radius  $\sim 30 \text{ }\mu\text{m}$ ) are injected by a dust dropper above the plate.

## 2. Determination of the dust charge

In low temperature laboratory plasmas, a dust grain acquires a negative charge [5] given by the balance of the ion and electron currents on its surface. To establish the currents, the commonly used model is the so-called ‘‘Orbital Motion Limited’’ theory [6] (OML) where one assumes that the dust grain behaves like a spherical probe. We write:

$$I_i(V) + I_e(V) + I_{ep}(V) = 0 \quad (1)$$

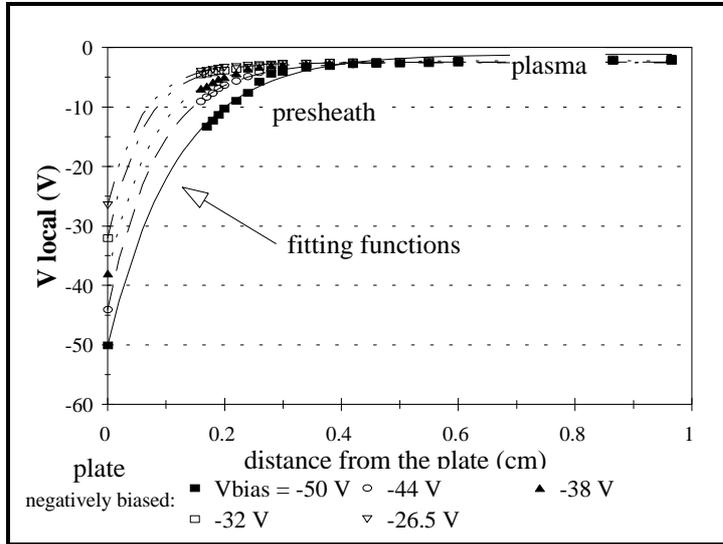
where  $I_i$ ,  $I_e$  are the currents of the ions and electrons Maxwellian populations and  $I_{ep}$ , the current of the primary electrons assumed to be characterized by an isotropic drifted Maxwellian population. (1) is fulfilled for the dust surface potential  $V_{dust}$ . Then, the charge of the grain simply is:  $Q_{dust} = C \cdot V_{dust}$ , where  $C = 4\pi\epsilon_0 r_d$  is the capacity of a sphere with radius  $r_d$ . The standard conditions for our experiment give in the plasma:  $V_{dust} = -16$  V and for  $r_d = 35 \pm 2$   $\mu\text{m}$ , the charge is:

$$Q_{dust} \sim 3.3 \cdot 10^{-5} e^- \quad (2)$$

## 3. Experimental results and discussion

### a) Charge determination

In general, we observe the suspension of 20-30 dust particles in the sheath edge of the metallic plate. They are trapped in a small horizontal plane parallel to the plate, of 2 or 3 centimeters in extent.



**Fig. 1.** Potential profiles measurements for 5 different bias of the plate embedded in the plasma

We have established the plate potential profile perpendicularly to its area, using a differential emissive probe [7]. Figure 1 gives what we obtain for 5 negative bias of the plate:  $V_{bias} = -50, -44, -38, -32, -26.5$  V. The last value is the floating potential. These measurements, well defined for the presheath-plasma region, are fitted by the function:

$$V(x) = -a \cdot \exp(-b \cdot x) - c \quad (3)$$

where  $a$ ,  $b$ ,  $c$  depend on  $V_{bias}$ . We have calculated the electric

forces applied on an isolated dust [8]: i) the ion Coulomb force where the ions transfer a part of their momentum through classical scattering ii) the ion collection force where the ions give their momentum through direct collisions and then iii) the opposed electric force due to the sheath-presheath of the plate. These three forces are stated with respect to the variable

$V = V_{\text{dust}} - V(x)$  where  $V(x)$  is given by (3) and  $V_{\text{dust}} = -16$  V. In these experimental conditions, we find that the ions forces are negligible. So, the gravitation force  $F_g$  is only balanced by the electric force  $F_e$ :

$$M_{\text{dust}} \cdot g = - Q_d \cdot \partial V / \partial x, \quad (4)$$

In the case where  $V_{\text{bias}} = -26.5$  V for instance, (4) is fulfilled at the height  $x_{\text{eq}} = 1.75$  mm corresponding to the local potential  $V(x_{\text{eq}}) = -3.8$  V, the electric field  $E = -\partial V / \partial x = 2.2$  kV/m and then  $Q_{\text{dust}}$  is given by  $M_{\text{dust}} \cdot g / E \sim 3.4 \cdot 10^{-5} e^-$  consistent with (2). The same calculation for the different  $V_{\text{bias}}$  gives:

$$Q_{\text{dust}} = (3.4 \pm 0.1) \cdot 10^5 e^-.$$

We have experimentally measured the successive levitation heights of an isolated dust for each  $V_{\text{bias}}$ . When  $V_{\text{bias}}$  increases, the levitation height increases too, until  $F_e = F_g$ . Indeed, the experimental position of the dust grain in the corresponding potential profile of Figure 1 gives graphically the equilibrium potential:  $V_{\text{eq}} = -3.3 \pm 0.2$  V. This value is slightly smaller ( $\sim 0.5$  V) than the calculated one. This result suggests that the dust grains charge is higher than (2) so  $V_{\text{dust}} = -16$  V is underestimated. The reason could be attributed to the limit of the OML theory stated for conditions where the dust grain is embedded in a plasma. The plasma parameters used in (1) are only approximations when dusts are trapped in a sheath potential profile.

By varying rapidly a discharge parameter (the discharge voltage for example), we can drive dust oscillations without damping (low argon pressure). For small oscillations around the balancing position  $x_0$ , the resonance frequency is given by:  $\omega = \left[ 1 / M_{\text{dust}} (dF / dx)_{x_0} \right]^{1/2}$  (5) where  $F = F_e + F_g$ . Measuring a typical frequency  $f = 15$  Hz ( $\omega = 2\pi f$ ), we find:  $Q_{\text{dust}} = 4 \cdot 10^5 e^-$ .

## b) Collision between two dust grains

Using a camera with a high magnification, we have studied a collision between two dust grains in a plane parallel to the plate. We have chosen an example where before the collision, one of the dust is moving while the second is motionless. Making the following assumptions: i) they undergo an elastic collision (no charge lost) and ii) the interaction force between the dust particles is a central force (excluding that they can behave like dipoles), we have checked the momentum and the energy conservation during the collision. In particular, the energy lost by the projectile dust (grain 1) is just transferred to the target dust (grain 2) after the collision. The classical scattering of a charge on another in the laboratory frame gives a relation between the projectile deviation angle  $\chi_0$  and the trajectory angle  $\psi_0$  of the target. This relation is:

$$\text{tg} \chi_0 = (m_2 / m_1) \text{tg}(2\psi_0), \quad (6)$$

where  $m_{1,2}$  is the mass of the dust grain 1 and 2. Measuring  $(\chi_0, \psi_0)$ , Equation (6) gives  $m_1 / m_2$ . We have chosen the best couple of radii  $(r_1, r_2)$  allowing us to find the theoretical couple  $(\chi_0, \psi_0)$  as close as possible to the experimental value. These radii are  $r_{1,2} = 32, 35$   $\mu\text{m}$ . In particular, injecting them in the classical equation:

$$1 + P^2 / r_m^2 - \phi(r_m) / 0.5 \mu\text{g}^2 = 0 \quad (7)$$

where  $P$  is the impact parameter of the dust grain 1,  $\mu$  the reduced mass,  $r_m$  the minimum approach radius,  $g$  the difference of the velocities before the collision (equal here to the velocity of 1) and taking  $\phi(r)$  equal to the screened Coulombian potential:

$$\phi(r) = (Z_1 Z_2 e^2 / 4\pi\epsilon_0 r) \exp(-r / \lambda_D) \quad (8)$$

where  $\lambda_D$  is the electron Debye length, we find the charge product of the dust grains 1 and 2:

$$\sqrt{Z_1 Z_2 e^2} = 4.5 \cdot 10^5 e^- \quad (9)$$

(the parameters  $P$ ,  $r_m$  and  $g$  are given by the experiment).

### c) Two dimensional dust self-organization observation

In special conditions, we observe a self-organization behavior of the dust grains. Most commonly, they form centered hexagonal structures in an horizontal plane where the typical distance separating the dusts is higher than the electron Debye length. The identification of the structure pattern is possible using two-dimensional (2D) geometrical studies like the Wigner-Seitz decomposition or the Delaunay triangulation. These 2D crystals are observed at low argon pressure ( $P_{ar} \sim 8 \cdot 10^{-4}$  Torr) where the gas flux regime is molecular. In our experimental conditions of a plasma produced by a hot cathode dc discharge, the question of the cooling of the dusts grains remains an open topic.

### References

- [1] Jin-Xiu Ma and M.Y. Yu: Phys. Rev. E **50**, 2431 (1994); A. Barkan, R.L. Merlino and N. D'Angelo: Phys. Plasmas **2**, 3563 (1995); M. Rosenberg: Phys. Plasmas **3**, 644 (1996); J.B. Pieper and J. Goree: Phys. Rev. E **77**, 3137 (1996); S. Benkada, P. Gabbai, V.N. Tsytovich and A. Verga: Phys. Rev. E **53**, 2717 (1996)
- [2] M. Horanyi: Annu. Rev. Astron. Astrophys. **34**, 383 (1996)
- [3] H.M. Thomas and G.E. Morfil, V. Demmel, J. Goree, B. Feuerbacher and D. Mohlmann: Phys. Rev. Lett. **73**, 652 (1994); H.M. Thomas and G.E. Morfill: Nature **379**, 806 (1996); A. Melzer, T. Trottenberg and A. Piel: Phys. Lett. A **191**, 301 (1994); A. Melzer, A. Homann and A. Piel: Phys. Rev. E **53**, 2757 (1996); J.B. Pieper, J. Goree and R.A. Quinn: J. Vac. Sci. Technol. A **14**, 519 (1996); Y. Hayashi and K. Tachibana: J. Vac. Sci. Technol. A **14**, 506 (1996); J.B. Pieper, J. Goree and R.A. Quinn: Phys. Rev. E **54**, 5636 (1996); V.N. Tsytovich: Phys. Uspekchi **40**, 53 (1997)
- [4] M. Carrere, L. Cherigier, C. Arnas-Capeau, G. Bachet and F. Doveil: Rev. Sci. Instrum. **67**, 4124 (1996)
- [5] O. Havnes, T.K. Aanesen and F. Melandso: J. Geophys. Research **95**, 6581 (1990); B. Walch, M. Horanyi and S. Robertson: IEEE Transactions on Plasma Sci. **22**, 97 (1994); T. Matsoukas and M. Russel: J. Appl. Phys. **77**, 4285 (1995)
- [6] F.F. Chen: *in* Plasma Diagnostics Technics, ed. by R.H. Huddlestone and S. Leonard, Chap. 4, Academic, N.Y. , 1965
- [7] W. En Yao, T. Intrator and N. Hershkowitz: Rev. Sci. Instrum. **56**, 519 (1985)
- [8] T. G. Northrop and T.J. Birmingham: Planet. Space Sci. **38**, 319 (1990); M.S. Barnes, J.H. Keller, J.C. Forster, J.A. O'Neill and D.K. Coultas: Phys. Rev. Lett. **68**, 313 (1992); T. Nitter: Plasma Sources Sci. Technol. **5**, 93 (1996)