TEST GRAINS AS A NOVEL DIAGNOSTIC TOOL

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What is a dusty plasma?

- a low temperature plasma containing small particles of diameters in nanometer and micrometer range
- particles acquire a net negative charge (at equilibrium floating potential)
- particles levitated in sheaths where electric force balances gravity
- particles can form liquid- and solid- like arrays (plasma or Coulomb crystal) which can undergo phase transitions
Forces on dust particle in plasma sheath

Figure 1: Schematic diagram of dust particle in plasma sheath
Forces on a dust particle

- Electric force
  \[ F_E = Z_d E \]

- Gravity force
  \[ F_g = \frac{4}{3} \pi a^3 \rho g \]

- Ion drag force
  \[ F_i = \pi a^2 n_i m_i v_i^2 \left( 1 - \frac{eZ_d}{am_i v_i^2} \right) \]

- Thermophoretic force
  \[ F_{th} = \frac{32}{15} \sqrt{\frac{\pi m}{8T}} a^2 \kappa \frac{\partial T}{\partial z} \]
where

- \( a \) is particle radius
- \( \rho \) is particle density
- \( Z_de \) is charge on particle
- \( m_i \) is ion mass
- \( n_i \) is ion density
- \( v_i \) is ion velocity in sheath
- \( T_e \) is electron temperature
- \( T \) is gas temperature
- \( m \) is mass of gas atoms
- \( \kappa \) is thermal conductivity of plasma
Experimental arrangement

**Figure 2:** Experimental chamber and image of test dust particles levitated above the electrode. The test grains are generated in the discharge (power up to 200W, pressure up to 1 torr) by electrode sputtering.
Using the force balance equation,\[ F_E + F_g + F_i + F_{th} = 0 \]
the equilibrium position has been calculated as a function of radius \( a \) (see figure 3) using following assumptions
- \( V_s \sim 60 \) V, linear variation of electric field in sheath
- \( v_i \) from sheath model
- \( T_e \sim 2 \) eV
- \( R = 2 \) g cm\(^{-3}\)
- \( dT/dz \sim 1-5 \) K cm\(^{-1}\) (varying with input power)
- \( Z_d \) calculated from OML theory
Equilibrium position vs. radius

Figure 3: Equilibrium height of dust particles above electrode $h_{eq}$, relative to height of sheath boundary $h_b$ as a function of particles radius for several values of ion plasma frequency,

$$\omega_i = 10^6 \text{ s}^{-1} \text{ (dashed)}, \quad 5 \times 10^6 \text{ s}^{-1} \text{ (dotted)}, \quad 10^7 \text{ s}^{-1} \text{ (solid)}$$

$$\omega_i = \frac{4\pi n_i e^2}{m_i}$$
**Alternative estimates of sheath width**

**Figure 4:** Electron temperature $T_e$ (points with error bars) measured using Langmuir probe; discharge emission (solid line); the dashed line shows the equilibrium position ($h_{eq} = 10.8$ mm) of test grains ($a \sim 350$ nm). Discharge conditions: $p = 90$m Torr, $P = 80$ W.
Sheath width as function of pressure

Position of sheath edge ($h_b$) vs pressure at different rf-input powers

- 35W
- 60W
- 100W
Visualisation of rf sheath

• Sufficiently small particles cannot achieve force equilibrium in the sheath - the sheath becomes a particle-free region
• Particles occupy pre-sheath and positive column
• Provides a visualisation of the sheath-plasma boundary - see Figure 5
Figure 5: The shape of the potential well above the confining electrode in a radio-frequency (rf) discharge with a printed-circuit board electrode system (Cheung et al., 2002) was visualised using fine dust grains that were generated in the discharge. The well shape was found to depend strongly on the confining potential.
Transient motion technique

\[ \Delta \phi = \frac{ma \Delta s + F(v_1)\Delta s_1 + F(v_2)\Delta s_2}{Z_d} \]

where 
\[ F = -\frac{4}{3} \delta m n_v \pi a^2 \nu \]

\[ \Delta \phi = f(r) \]

Where \( f_0 \) is the resonant frequency
And \( E \) is the electric field gradient

\[ Z_D = \frac{(2\pi f_0)^2 m}{E} \]
Effect of hot electrons in sheath

Figure 6: Square root of distance of particle from sheath edge as a function of particle radius.

$\sqrt{h - h_{eq}}$

$P=80$ mTorr

$P=40$ mTorr

$R_d \sim \sqrt{h - h_{eq}}$
Figure 7: Potential profile measured by a Langmuir probe, and by transient motion analysis
Conclusions

- as particle radius decreases, equilibrium position moves closer to edge of sheath
- sufficiently small particles avoid sheath region, occupying presheath and positive column, providing visualisation of sheath
- hot electrons affect equilibrium position
- potential and electric filed profiles determined from transient motion analysis

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References
A.A. Samarian and B.W. James, Phys Letters A, 287 (2001) 125
Figure 8: Radial electric field derived from results in figure 7.