Micro-particles as probes
for plasma and sheath diagnostics

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Graduate Summer Institute
„Complex Plasmas“

University of Greifswald
August 11, 2010

Group Plasma Technology
introduction

Dusty plasmas – an interesting feature of complex plasmas

Complex plasmas are distinct from conventional plasmas by the presence of
• additional plasma constituents,
• by particle correlations,
• or by interactions with solid surfaces,
which decisively influence the behavior of the plasma and provide important and novel properties.

Complex plasma systems which contain, for example, colloidal nano/microscopic particles (dust) have recently been widely discussed in the physics and chemistry of plasmas, ionized gases, space physics, and astrophysics, plasma diagnostics, as well as in materials research and engineering.

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introduction

• astrophysics
  (formation of stars, comets, planetary rings)
  Goertz, Mendis, Sedlmayer, Morfill …

• basic research: plasma crystals
  Piel, Morfill, Goree, Fortov, Melzer, Lampe …

• dust as fault in semiconductor processing
  Selwyn, Boufendi, Winter, Kroesen, Hollenstein, Shiratani …

• generation and modification of powders (technological application)
  • micro-probes for diagnostics

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introduction  

method:
experimental investigation of interaction between plasma parameters and the behaviour \( (r, t) \) of dust particles in the plasma for using in diagnostics

aims:
- electrostatic probes
  determination of local electric fields, especially in plasma sheath
- thermal probes
  fluorescent particles for the measurement of the energy fluxes
- micro-substrates
  investigation of reactive processes on microscopic surfaces, diagnostics of radicals in plasma
- force probes
  determination of momentum transfer / forces

modeling of particle charging

effect of additional plasma sources on the behaviour of micro-particles
(ion beam source, dc-magnetron, AE, …)
dust particles as electrostatic probes
dust particles as electrostatic micro-probes

\[ I_e, I_i \]

\[ Q = f(T^1_e, T^2_{ie}, n_0, m_{i, e}, n_{e, i}, n_0) \]

- charging depends on plasma parameters
- dynamic of dust (movement)
- equilibrium (position)

\[ \sum_{i} F_i = 0 \]
\[ \sum_{i} F_{eq} = ma \]

⇒ dust grains as test particles (probes) in plasma surrounding
dust particles as electrostatic micro-probes

forces onto particles

1. gravitation
2. neutral drag force (viscosity)
3. ion drag force
4. electrostatic force (E-field)
5. thermophoresis (temperature gradient)
6. photophoresis (radiation)
7. inter grain force (Coulomb)

wall (1): \( E = 100 \text{V/m} \)
sheath (2): \( E = 10^4 \text{V/m} \)
Dust particles as electrostatic micro-probes forces onto particles

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A. Melzer
Only the sheath region provides electric fields that are strong enough to levitate dust.

→ dust sediments into the sheath, crystals are 2 D or 2.5 D

→ resonance frequency yields $Q / M$

\[
Q(z_0)E(z_0) = mg
\]

\[
m\ddot{z} + m\beta \dot{z} + Q(z)E(z) = F_{\text{ext}}
\]

Assumption: constant charge

Linear electric field

\[
E(z) = E(z_0) + E'(z - z_0)
\]

Potential well

\[
\frac{1}{2} m \alpha_0^2 (z - z_0)^2 = \frac{1}{2} Q_0 E'(z - z_0)^2
\]

Resonance frequency

\[
\omega_0^2 = \frac{Q_0 E'}{m}
\]
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\[ V_{pl}, n_n, n_e, n_i, kT_n, kT_e, kT_i \]

\[ v_i \]

sheath boundary

\[ E \]

\[ F_E, F_{th} \]

\[ F_g, F_i \]

radius = \( R_d \)

charge = \( Z_d e_0 \)

\[ z_0 \]

\[ z \]

rf powered electrode


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A. Samarian et al.

Bulk plasma

Sub-micron particles

Sheath edge ($d_{sh}$)

2.00 micrometer dust

3.04 micrometer dust

3.87 micrometer dust

4.89 micrometer dust

6.76 micrometer dust

Powered electrode

Probing of sheath electric field at different heights

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dust particles as electrostatic micro-probes

asymmetric rf plasma *PerPIEx*

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*Micro-particles as probes for plasma and sheath diagnostics*

08/11/2010
M. Wolter, M. Haass, T. Ockenga, J. Blazek, H. Kersten

"Micro-Particles as Electrostatic Probes for Plasma Sheath Diagnostics",


\[ p = 8 \text{ Pa}, \quad V_{\text{bias}} = 50 \ldots 200 \text{ V} \]
\[ r_p = 4.8 \mu\text{m} \]
M. Haass,
"Investigation of Plasma-Particle Interaction in Front of Vertical Electrodes",

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\[ V_{pl} \sim 20V \]

\[ m_d \sim 7.9 \times 10^{-13} \text{kg} \]
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**dust particles as electrostatic micro-probes**  
adaptive electrode

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**Graphs and Figures:**
- Plots showing the relationship between frequency and amplitude.
- Graph showing the resonance frequency as a function of vertical position for different Ar-pressure values.
- Graphs illustrating the emission position as a function of vertical position for different particle sizes.

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**Text:**
- dust particles as electrostatic micro-probes
- adaptive electrode
- H. Kersten

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**dust particles as electrostatic micro-probes**

**adaptive electrode**

superposition of harmonics:

\[ F_0 \cos(\omega t) = m \frac{d^2 z}{dt^2} - Qz \frac{dE(z)}{dz} \]

equilibrium:

\[ QE = mg \]

experiment:

\[ \omega = 2\pi(az + b) \]

solved for \( E(z) \):

\[ E(z) = E(0) \exp \left( -\frac{1}{g} \int_0^z \omega_0^2(\zeta) d\zeta \right). \]

resonance frequency at small amplitude:

\[ \omega_0^2(z_0) = Z(z_0) \frac{e_0}{m} \frac{dE(z)}{dz} \bigg|_{z_0} = -\frac{g}{E(z_0)} \frac{dE(z)}{dz} \bigg|_{z_0}, \]

results in:

\[ \frac{\omega_0^2(z)}{g} = -\frac{dE(z)}{dz} \frac{1}{E(z)} \]

- friction neglected (neutrals, ions)
- integration of E-field along sheath yields sheath voltage (bias)

**Graph**

- electric field strength \( E(z) \) [V/m]
- vertical position \( z \) [mm]

**Legend**

- 1.0 Pa
- 2.5 Pa
- 5.0 Pa
- 7.5 Pa
- 10 Pa

**Legend**

- \( P_e = 10 \text{W}, \) parameter: Ar-pressure

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dust particles as electrostatic micro-probes
adaptive electrode

Basner, R., Sigenerger, F., Loffhagen, D., Schubert, G., Fehske, H., Kersten, H.,
"Particles as probes for complex plasmas in front of biased surfaces",

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dust particles as electrostatic micro-probes

falling dust particles
due to gravitation and neutral drag

\[ F(z) = m \ddot{z} = -mg - \beta \dot{z} \]

\[ z(t) = z_0 - \frac{mg}{\beta} \left( t - \frac{m}{\beta} \left( 1 - e^{-\frac{\beta t}{m}} \right) \right) \]
dust particles as electrostatic micro-probes

\[ F(z) = F_{el}(z) + F_n(z) - F_g - F_{ion}(z) \]

\[ V_{bias} = V_{pl} - V_{pixel} = 20V - (-50V) = 70V \]

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plasma on, E5 at -50V

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dust particles as electrostatic micro-probes

dust particles
in a striated dc-discharge
due to electrostatic field
In order to measure the electric field structure at any position in the plasma sheath *without* the plasma being changed or disturbed an additional, non-electric, force is introduced which does not alter the plasma conditions, but which does allow for manipulation of the particle position through the sheath. This additional force is generated by (hyper-)gravity, induced by a centrifuge.
neglecting $F_i$ and $F_{th}$ because they are small in comparison to $F_g$ and $F_{el}$

balance of forces at equilibrium position $z = z_0$:

$$Q_p(z_0) \cdot \vec{E}(z_0) = m_p \cdot \vec{g}$$  \hspace{1cm} (1)

idea:
when the equilibrium position of the particles is changed to $z$ by increasing the apparent gravitational acceleration up to $g^*(z)$ (given in units of gravitational acceleration $g$), $Q_p(z)E(z)$ can be determined as function of $z$
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\[ E(z) = \frac{m_p g}{Q_p(z_0)} \exp\left\{ \int_{z_0}^{z} \frac{\omega_0^2(\xi)}{g(*)(\xi)} d\xi \right\} \]

- determination of \( Q_p(z_0) \) by eq.(3), e.g. measurement of \( n_i(z_0) \) and \( \omega_0(z_0) \) under “normal” gravity condition (g):

\[ \omega_0(z_0) = 17.3Hz \text{ by resonance method} \]
\[ n_i(z_0) = 5.7 \times 10^{14} m^{-3} \text{ by Langmuir-probe measurement} \]

\[ Q_p(z_0) = 6 \times 10^3 e_0 \]
• generation of $g^*(z)$ and measurement of $\omega_0(z)$ are necessary

  ➔  “hyper”-gravity conditions induced by a centrifuge

  ➔  measurement of $\omega_0(z)$ at different heights $z$
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dust particles as electrostatic micro-probes

illumination and observation of probe particles

plasma chamber
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"hyper gravity"

Name des Vortragenden

Vortragstitel

Datum

08/11/2010
dust particles as electrostatic micro-probes

"hyper gravity"

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dust particles as electrostatic micro-probes

height of confinement is influenced by $g^*$
- Dependences on $z$ are used to calculate $Q_p(z)$, which increases towards the rf-electrode due to decreasing ion density and increasing collection of secondary electrons.

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Electric field profile in the sheath:

- $E(z)$ is linear over a large part of the sheath.
- Close to the sheath edge, the behaviour is non-linear.
- Absolute values of E-field show good agreement with literature.
dust particles as force probes
dust particles as force probes

Moving dust particles due to ion drag

dust particles as force probes

synthesized a-C:H particles (~100nm)
show vortices and voids due to the **ion drag**
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Ion drag

EC/A 125, IOM Leipzig

ion source

CCD, video, OES

aperture

Langmuir-probe

thermal probe

Ar

p

TP-system

rf-generator

PULVA 2

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dust particles as force probes

• investigation of the influence of an external ion beam

• the effect of such an ion beam is threefold:

  # change of the sheath structure and the electric field
  (plasma density in trapping region),

  # re-charging of the dust particles (additional positive ion supply),

  # variation of the ion drag force (Coulomb interaction, momentum transfer)

• Ar, 2.2 Pa
• rf-plasma, 5 W
• large ring, SiO$_2$ ~1µm
• particle injection

• Ar, 2.2 Pa
• rf-plasma, 5 W
• large ring, SiO$_2$ ~1µm
• ion beam on / off, 200 V

Kersten, H., et al.
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ion drag

particles in external ion beam
(IOM Leipzig)


S. Bornholdt

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Hole covered by screen
No ion beam

\( p = 3 \text{ Pa} \)
\( V_{\text{bias}} = 146 \text{ V} \)
hole open

\[ p = 3 \text{ Pa} \]
\[ U_{\text{bias}} = 146 \text{ V} \]
Fion

Fion

Fion

p = 3 Pa
U_{bias} = 146 V
dust particles as force probes

two components of ion drag force

$F_i/\pi a^2 m_i n_i$ vs. $v/v_{th}$
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T. Brandt

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VIBEX:
Vertical Ion Beam EXperiment

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08/11/2010
dust particles as force probes

Trottenberg, T., Schneider, V., Kersten, H.,
„Measurement of the force on microparticles in an energetic ion beam”,

Schneider, V., Trottenberg, T., Teliban, I., Kersten, H.,
„An experiment for the investigation of forces on microparticles in ion beams”,
dust particles as thermal probes
dust particles as thermal probes
energetic processes on surface

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Dust particles as thermal probes

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Plasma measurements:
- Exposure time: 5s
- Number of accumulations: 20

Calibration measurements (oven):
- Temperature steps ≤ 0.4 °C
- $dT/dt \leq 1/260$ K/s
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- **Name des Vortragenden**: H. Kersten
- **Vortragstitel**: Micro-particles as probes for plasma and sheath diagnostics
- **Datum**: 08/11/2010

**Graphs**
- Two graphs show the relationship between particle temperature $T\,[^{\circ}\text{C}]$ and power density $P_{\text{ff}}$ [W] for different pressures $p$.
- For $p = 10\, \text{Pa}$, the temperature increases linearly with power density.
- For $p = 20\, \text{Pa}$, the temperature also increases linearly, but at a slower rate.
- For $p = 30\, \text{Pa}$, the temperature increases but with a more pronounced curvature.
- For $p = 50\, \text{Pa}$, the temperature remains relatively constant with small fluctuations around $40\,^{\circ}\text{C}$. 

**Caption**: The graphs illustrate how dust particles can be used as thermal probes for plasma and sheath diagnostics.
dust particles as thermal probes

Contributions of energy influx at substrate surface:

- irradiation (plasma, walls, sources)
- kinetic energy of charge carriers (electrons, ions)
- energy of neutrals (kinetic energy, excitation energy, heat of adsorption, condensation, resp.)
- exothermic chemical reactions
- recombination (charge carriers, atoms)
- external heating

Energy losses at substrate surface:

- radiation (environment)
- heat conduction and convection (substrate holder, gas)
- desorption
- endothermic chemical reactions
- sputtering of particles and secondary electron emission
- external cooling

Maurer, H.R., Basner, R., Kersten, H.,
“Temperature of particulates in low-pressure rf-plasmas in Ar, Ar/H2 and Ar/N2 mixtures”,
Contrib. Plasma Phys. 2010, accepted

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summary
Complex plasma systems which contain, for example, colloidal nano/microscopic particles (dust) have recently been widely discussed in the physics and chemistry of plasmas, ionized gases, space physics and astrophysics, plasma diagnostics, as well as in materials research and engineering.

Dust (test) particles can be used as probes for various physical quantities as electric fields, energy fluxes, momentum transfer, etc. in complex plasmas.