XXII. Erfahrungsaustausch  
Oberflächentechnologie mit Plasma- und Ionenstrahlprozessen  

Neueste Entwicklungen zum Aufbau einer Plasmadiagnostik mittels optisch gefangener Mikropartikel

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Microparticles as probes

- research on the plasma sheath
  - analysis of the electric field
  - particle charge
  - forces (e.g., ion drag)

- basic research
  - several forces (e.g., thermophoretic force, neutral drag force)
  - particle interactions
  - ion wake

- dual frequency discharge
  - modification of the ion energy / density

P. Hartmann et al., "Dust as probe for horizontal field distribution in low pressure gas discharges", Plasma Sources Sci. Technol. 23(2014), 045008
Principle of Optical Tweezers

- focused beam causes a force towards the focal point
- “single beam trap” (high NA necessary)

Experimental Setup

- asymmetric RF discharge (13.56 MHz)
- cooled, powered electrode (Ø = 10 cm)
- electrode / plasma is movable along x-axis

Particle dispenser

Camera #1 (view from the top)

QPD and CCD-camera

Camera #2 (view from the side)

Illuminating laser 660nm

10x-long-distance microscope
Trapping and Manipulation

- successful stable trapping of particles with 0.5 W – 3 W
- successful movement of particle through plasma
- successful movement of particle through sheath
- successful trapping in a ring-electrode with many moving particles
- successful trapping in vacuum (plasma turned off) down to 0.1 Pa
Force Measurement

- for small deviations \( \Delta x \) the force can be assumed as \( F_{\text{opt}} = -\kappa \Delta x \) with the optical trap stiffness \( \kappa \)

- force measurements over a precise position detection of the trapped object
- external force \( F_{\text{ext}} \) of magnitude \( F_{\text{max}} \) can be measured from the deviation \( \Delta x \)
in a ray-optic approximation, the microparticle acts as a simple lens producing an intensity pattern, which depends on the object position

a quadrant photodiode (QPD) is positioned in the optical axis

Position Measurement

\[
\begin{align*}
\Delta x &= \frac{(Q_1 + Q_2) - (Q_3 + Q_4)}{Q_1 + Q_2 + Q_3 + Q_4} \\
\Delta y &= \frac{(Q_1 + Q_4) - (Q_2 + Q_3)}{Q_1 + Q_2 + Q_3 + Q_4} \\
\Delta z &\cong Q_1 + Q_2 + Q_3 + Q_4
\end{align*}
\]

Position Measurement

detector (QPD)

CCD-camera

detector and CCD-camera
Calibration
short pulse of the trapping laser causes a falling distance of the particle
\[ \Delta x = \frac{1}{2}gt^2 \], where \( t \) is the off-time and \( g \) the gravitational acceleration

the difference \( \Delta U \) in the detector signal should yield the conversion \( m/V \)

example:
\[
\begin{align*}
 t &= \frac{1}{1600} s = 0.625 \, ms \\
 \Delta x &= 1.95 \, \mu m
\end{align*}
\]

from camera
\[
\begin{align*}
 t &= 0.667 \, ms \\
 \Delta x &= 2.13 \, \mu m
\end{align*}
\]

from detector
\[
\begin{align*}
 t &= 0.740 \, ms \\
 \Delta x &= 2.74 \, \mu m \\
 \Delta U &= 36 \, mV
\end{align*}
\]
Spectral Analysis

- the Langevin equation for an optically trapped particle in a gas

\[ \ddot{x} + \Gamma_0 \dot{x} + \Omega_0^2 x = \frac{F_{\text{therm}}(t)}{m} \zeta(t), \]

\[ F_{\text{therm}}(t) = \sqrt{2k_BT}\gamma, \]

\[ \langle \zeta(t) \rangle = 0, \langle \zeta(t)\zeta(t') \rangle = \delta(t - t') \]

and

\[ \Gamma_0 = \frac{\gamma}{m}, \quad \Omega_0 = \sqrt{\kappa/m} \]

- this leads to the power spectral density (PSD)

\[ S(\omega) = \frac{2k_BT}{m} \frac{\Gamma_0}{(\Omega_0^2 - \omega^2)^2 + \omega^2\Gamma_0^2} \]


with the particle mass

\[ m \approx 1 \cdot 10^{-12} \, \text{kg} \]

\[ \kappa = \Omega_0^2 m \]

\[ \approx 7.6 \, \text{pN/\mu m} \]
Stiffness-Calibration Method

- stiffness parameter in x-direction determined from one particle at different laser powers at 2 Pa
Exemplary Measurements
Exemplary Measurements

Plasma off → Plasma on

Plasma on → Plasma off
Exemplary Measurements
Outlook

- verification of trap calibration (position calibration, trap parameter)

Next steps towards diagnostic:

- the force acting on the particle is determined from the position measurement
  - the particle charge is either measured with the resonance method or estimated from simulations
    - from the measured forces and the particle charge the electric field in the sheath is determined at different positions in the sheath

- systematic measurements in the plasma (mainly in the sheath region)

- several studies (forces, particle interactions, ion wake etc.)
- measurements in a dual frequency discharge (force change due to variation of the ion density / ion energy)
Thank you!