Sheath phenomena in dusty plasmas

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SHEATH PHENOMENA IN DUSTY PLASMAS

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Chapter 1

Introduction

1.1 Plasmas

Plasma is the most common state of matter. Tonks and Langmuir have introduced the term "plasma" for the first time in 1929 [1]. Plasma is a (partially) ionized gas, i.e. a substance containing free electrons and ions. One of the most important features of a plasma is its quasi-neutrality. If a deviation from neutrality occurs, the strong electrostatic interaction between negative and positive charges leads to currents, which restore the neutrality. There are many different types of plasma - both natural (sun, aurora, nebulae etc.) and artificial. Many ways of creating plasmas exist. The most common way of plasma generation is by an external electric field. The electric discharges can be classified based on the temporal behavior of the electric field:

- dc (direct current) discharge;
- ac (alternating current) discharge;
- pulsed discharge.

The ac discharges are generally classified in three groups, based on their frequency $\nu_{\text{disch}}$:

- low frequency: $\nu_{\text{disch}} \ll \nu_e, \nu_i$;
- radio-frequency - in the MHz region (1 – 100MHz): $\nu_i < \nu_{\text{disch}} < \nu_e$;
- microwave - in the GHz region: $\nu_{\text{disch}} \gg \nu_e, \nu_i$.

Here, $\nu_e$ and $\nu_i$ are the electron and ion plasma frequency, respectively, defined in detail in section 2.2.1.2.
1.2 Dusty plasma. Development of the field

Ionized gases containing small particles of solid matter are called dusty (complex) plasmas. In the last decades there has been a growing interest in this field. This interest rose in two very different fields in physics - the astrophysics and the industrial plasma research, in particular microelectronics.

Initially, the interest in dusty plasmas arose in the field of astrophysics, as dust is present in many astrophysical environments (interstellar medium [2], nebulæ [3], comet tails, planetary rings [4]). Another fundamental field, in which the dust presence has an important role, is the physics of the atmosphere. Dust appears as aerosols in the atmosphere or as essential constituent of the noctilucent clouds. Due to environmental awareness, this novel interest is rising.

The largest "kick" in the increase of the interest in dusty plasmas came from a completely different field - the semiconductor industry. Dust appeared to be a critical issue in the development of microelectronics. As the semiconductor industry aims at miniaturization, the contamination of the processing plasma with even very small particles became crucial. Initially it was considered that contamination originates from external sources, but soon it was discovered that the plasma itself can create dust particles. Many efforts have been dedicated to investigate and understand the particle growth, charging and transport in plasmas [5, 6].

In the meantime, positive aspects of the dusty plasma have been discovered. For example the specific feature of dusty plasma to decrease the density of free electrons and, respectively, to increase their energy can be used for dust-plasma-enhanced chemical vapor deposition [7].

Another area showing high interest in dusty plasmas is the solar cell industry. Initially this industry (just like the microelectronics) was interested in removal of the dust, which grows in glow discharges in silane. Later it has been shown that the incorporation of nanometer-sized dust particles in the amorphous silicon film can substantially increase the stability of the solar cell [8].

Another application of the plasma-produced particles is found in catalysis. Small clusters (several nm) of palladium (good catalyst) can be deposited on the surface of particles, grown in the plasma. The resulting cauliflower morphology is very efficient for catalytical application [9].

Also plasma processing of externally injected particles is possible. By coating them in a depositing plasma, the properties of the injected grains and the coating layers can be tailored. For example, coating iron powder particles can enhance their optical properties [10–12]. Such particles can be useful as toners in copying machines. Due to the low throughput in low-
pressure plasmas, these processes are of industrial interest only for high-value added materials.

Apart from their industrial impact, dusty plasmas appeared to be of fundamental interest. First Ikezi [13] theoretically predicted formation of Coulomb dust lattices. Several years later Coulomb crystals were observed in experiments [14–18]. The easy and cheap diagnostics, which can be used for investigation of the Coulomb crystals, make them attractive model systems for solid-state crystals. Processes as phase transitions [19] or lattice vibrations [20] have been investigated.

The interaction between dust particles and plasma can be used also as a diagnostic tool for characterization of the electric field profile in the plasma sheath [21, 22].

1.3 Dust in the plasma sheath

In dusty plasmas, the particles can levitate in the plasma bulk or in the plasma sheath, dependent on the gravitational conditions and on their size. Micrometer-sized particles immersed in typical laboratory plasmas get highly negatively charged. Unless in micro-gravity conditions, they are trapped in the plasma sheath. In figure 1.1 a schematic image of a RF dusty plasma is shown. The bulk plasma is quasi-neutral. The dust particles are trapped in the sheath where electric fields are present. The position of the particle is determined by the equilibrium of the upward electric and the downward gravitational forces.

In the plasma sheath, a dust particle is subject of other forces too: ion drag force, neutral drag force, thermophoresis, and radiation pressure. This makes their dynamics quite complicated and results in many interesting phenomena. The aim of this thesis is to give insight in the mechanisms of several sheath phenomena in dusty plasma, in particular: void formation, "friction-less" orbital motion and counter-phase oscillations.

Voids in the bulk plasma have been observed both under normal gravity [23, 24] and microgravity [25] conditions. Their presence in the plasma sheath has been observed even earlier [26], however not identified as such. A lot of research has been dedicated to the voids in the bulk dusty plasma, while those developing in the plasma sheath have been neglected. Part of this thesis, Chapter 4, is dedicated to filling this niche in the voids investigation.

Even though there is almost no published information in the literature on observed orbiting of dust particles, private communication shows that this is not an isolated effect. A recent publication is dedicated to this topic [27]. Part of this thesis, Chapter 5, is dealing with this particle behaviour.
Chapter 1

Figure 1.1: Schematic presentation of the sheath region of a plasma with micrometer-sized (heavy) dust particles in gravitational conditions

A lot of research has been dedicated to driven particle oscillations [28–31]. The investigation of the particle oscillations concerns usually the frequency dependence of the amplitude. No information on the phase of the oscillations is presented. An experimental technique for determination of the dust charge in the sheath, based on driven particle oscillations, has been proposed [28]. Usually, a linear electric field in the sheath is assumed. As we will see in Chapter 6, where observations of counter-phase oscillations are analyzed, the assumption of linear electric field is not always valid.

1.4 Scope and structure of the thesis

As already mentioned, this thesis deals with studies of several new phenomena, discovered in experiments performed with micrometer-sized dust particles immersed in radio-frequency capacitively coupled plasma in argon. The investigation of these phenomena, observed in the dusty plasma sheath, aims at understanding of their mechanisms.

The work presented in this dissertation is performed in the group Elementary Processes in Gas discharges (EPG) in the Faculty of Applied Physics of
Introduction

the Eindhoven University of Technology, The Netherlands.

In Chapter 2, selected topics of the basic theory of dusty plasma are reviewed, as this theory is essential for the understanding of the experiments presented in this dissertation. As the experiments are performed with micrometer-sized particles, special attention is payed to the dynamics of these particles in the plasma sheath.

In Chapter 3, the main features of the experimental set-up, in which the experiments have been performed, are described. The results of Langmuir probe and Plasma Impedance Monitor measurements are presented in order to characterize the plasma, in which the experiments with dust grains are performed.

In Chapter 4, observations on voids in 2D sheath dust clouds are presented. The effect of RF power, pressure and trapping depression size on the void formation have been investigated. Two different models explaining only the cloud volume change, but not the reason for void formation, are described. Also two numerical fluid models are presented. Analyzing the results and comparing the physics included in the two fluid models gives insight in the possible physical reasons for the void formation in the sheath dust cloud.

In Chapter 5, the observed orbital motion of dust particles is presented. The specific position of the orbiting particles with respect to the ”normal” dust cloud, the power and pressure dependence of their velocities as well as some specific behavior as spinning and transitions between orbits are analyzed in order to find the force or the mechanism responsible for this ”frictionless” motion. Based on the analysis of the orbiting motion, it is suggested that the mechanism is connected to the ion flow in the plasma sheath. Comparison with previous experiments dealing with rotational motion of dust particles in a plasma shows that none of the existing theories is able to explain the orbiting described in this dissertation. Further, different particle forms are considered and it is shown that with the contemporary knowledge of the plasma-dust dynamics a symmetric particle could not perform orbiting motion. Finally, two possible mechanisms are proposed - sailing and spinning-induced orbiting. It is shown that only the sailing can be responsible for orbiting in the plasma sheath in laboratory plasma.

In Chapter 6, an experimental study of driven vertical oscillations of dust particles levitating in the plasma sheath is presented. After giving a brief theoretical background of the field development until now, the first observation of counter-phase oscillations of particles with different masses as well as the observation of a particle not affected by the power modulation are presented. The following analysis of the equation of motion of the particle, which does not feel the power modulation, shows that at this position the
electric field does not change with power. A sheath model shows agreement
with the experiment.

Finally, in Chapter 7 some conclusions are drawn from the work presented
in this thesis.

1.5 Publications

1.5.1 Publications related to chapters of this thesis

- "Evolution of a Dust Void in a Radio-Frequency Plasma Sheath" R.P.
  Dahiya, G.V. Paeva, W.W. Stoffels, E. Stoffels, G.M.W. Kroesen, K.
  125001, 2002

- "Rotation of Particles Trapped in the Sheath of a Radio-Frequency Ca-
  pacitively Coupled Plasma" G.V. Paeva, R.P. Dahiya, G.M.W. Kroesen

- "Dust void formation above rectangular and circular potential traps in
  a RF plasma" R. Vrancken, G.V. Paeva, G.M.W. Kroesen and W.W.
  Stoffels, to be published

- "Counter-phase oscillations of dust particles in a RF plasma sheath"
  G.V. Paeva, V. Vyas, M. Kushner, G.M.W. Kroesen and W.W. Stoffels,
  to be published

1.5.2 Contributions to international conferences

- 25th ICPIG International Conference on Phenomena in Ionized Gases,
  17-22 July, 2001, Nagoya, Japan; G.V. Paeva, P.R. Dahiya, E. Stoffels,
  W.W. Stoffels, and G.M.W. Kroesen "Processing of dust particles in

- 5th European Workshop on Dusty and Colloidal Plasmas, 23-25 Au-
  gust, 2001, Postdam, Germany:

    Kroesen "Voids in argon, oxygen and argon-oxygen plasmas" (Oral
    presentation)

    Kroesen "Spinning and orbiting of dust particles in low pressure
    RF plasma" (Poster presentation)
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- 10th workshop on the physics of dusty plasmas, 18-21 June, 2003, St. Thomas, USA Virgin Islands; G.V. Paeva "Experimental investigation on behavior of dust particles in the RF sheath" (Oral presentation)
Chapter 2

General theory

2.1 Introduction

In this chapter we will discuss some main topics of the theory of dusty plasmas, which are important to understand the experiments presented in this thesis. In section 2.2, a description of the commonly used radio-frequency plasma is given - some basic plasma parameters are introduced and the theory of plasma sheath is discussed. Section 2.3 will deal with the charging processes of dust particles immersed in the plasma. In section 2.4, the forces acting on charged dust particles levitating in the plasma sheath are described and estimated. Finally, in section 2.5, the collective behavior of dust cloud is characterized.

2.2 Radio frequency (RF) plasma

This section will deal with the theory of RF plasmas. We introduce some basic plasma parameters and we estimate their values for a typical capacitively coupled RF discharge. As the dust particles in our experiments are levitating in the plasma sheath, we discuss this region of the plasma more extensively.

The radio-frequency plasma is one of the most commonly used types of plasma. In this type of plasma, a high frequency (MHz) sinusoidal voltage is applied. This voltage creates an electric field, in which charge carriers are accelerated. These charge carriers participate in further ionization of the gas. Basically, there are two different types of RF plasma, dependent on their coupling:

- capacitively coupled plasma (CCP): the voltage is applied at the electrodes and the electrons and ions are accelerated in the electric field;
• inductively coupled plasma (ICP): the electromagnetic field is generated by a coil and the plasma acts as a secondary induction coil.

As the plasma used in the experiments in this thesis is capacitively coupled, we give a schematic view of this type of plasma source in figure 2.1. The plasma is created by applying an electric field between two electrodes (one of the electrodes is grounded, at the other RF potential is applied). A capacitor prevents any DC current. An essential part of the CCRF plasma source is the matching network. Power transfer from the power generator to the plasma with the lowest possible losses requires the source impedance $50\Omega$ (generator) and the load impedance (plasma) to be of the same value (resonance). This is achieved with the matching network.

![Figure 2.1: Schematic view of a capacitively-coupled RF plasma source](image)

### 2.2.1 Basic parameters of the plasma

Here we introduce some important parameters, commonly used to define the plasma.

#### 2.2.1.1 Debye length

As we have mentioned earlier, the bulk plasma is quasi-neutral. The characteristic distance, on which deviations from quasi-neutrality can occur, is called the Debye length. The electron and ion Debye length $\lambda_{D,e,i}$ are defined as:
where \( \varepsilon_0 \) is the dielectric constant in vacuum, \( k \) - the Boltzmann constant, \( T_{e,i} \) - respectively, the electron and ion temperature, \( e \) - the electron charge and \( n_\infty \) - the plasma density. In a typical low-pressure capacitively coupled RF plasma, the electron temperature is \( T_e \approx 3eV \), the ion temperature is \( T_i \approx 0.03eV \) and the plasma density is of the order of \( n_\infty = 5 \times 10^{15} m^{-3} \).

Substituting these values in formula 2.1, we calculate the electron Debye length to be of the order of \( \lambda_{D_e} = 0.18 \text{mm} \) and the ion Debye length \( \lambda_{D_i} = 0.02 \text{mm} \). For dusty plasmas, a linearized Debye length is often defined by:

\[
\frac{1}{\lambda_D^2} = \frac{1}{\lambda_{D_e}^2} + \frac{1}{\lambda_{D_i}^2}.
\]

For non-equilibrium plasmas \( (T_e \gg T_i) \), as in our case, the linearized Debye length is closer to the ion Debye length.

### 2.2.1.2 Plasma frequency

Another important parameter of the plasma is the plasma frequency. We distinguish plasma frequencies for electrons and for ions. These parameters correspond to the typical electrostatic oscillation frequency appearing as a result of small charge separation in the plasma for electrons \( (e) \) and ions \( (i) \), respectively:

\[
\omega_{e,i} = \sqrt{\frac{n_\infty(e,i)Z_{e,i}e^2}{m_{e,i}\varepsilon_0}}.
\]

The values of the plasma frequencies for electrons and argon ions in typical plasma conditions \( (n_\infty = 5 \times 10^{15} m^{-3}) \) are given in table 2.1.

<table>
<thead>
<tr>
<th>particle</th>
<th>plasma frequency ( \nu = \omega/2\pi )</th>
</tr>
</thead>
<tbody>
<tr>
<td>electron</td>
<td>635 MHz</td>
</tr>
<tr>
<td>ion</td>
<td>2.35 MHz</td>
</tr>
</tbody>
</table>

Table 2.1: Plasma frequency

The driving frequency for typical RF discharge \( (13.56 MHz) \) is between the ion and electron frequency \( \omega_i < \omega \ll \omega_e \). This means that the electrons oscillate with the field, while the ions follow the time averaged field.
Chapter 2

2.2.1.3 Mean free path

The last parameter we introduce in this part is the mean free path. This is the distance, which a particle 1 (ion, electron, neutral, molecule) can travel in the plasma without undergoing collision with another particle 2:

$$l_{mfp,1} = \frac{1}{n_2 \sigma_{12}},$$  \hspace{1cm} (2.4)

where $n_2$ is the number density of the particles 2 and $\sigma_{12}$ is the cross section for the corresponding collision of particle 1 with particles 2. For our purposes, the most important collisions are the ion-neutral ones. In argon plasma, for ions at the Bohm velocity (at $T_e = 3 \text{eV}$) the momentum transfer cross-section is $\sigma_{in} \approx 8 \times 10^{-19} \text{m}^2$ [32]. The neutral density $n_n$ is calculated from the pressure, assuming the ideal gas law:

$$n_n = \frac{p}{k_B T_n},$$ \hspace{1cm} (2.5)

where $p$ is the gas pressure, measured in Pa, $k_B$ - the Boltzmann constant and $T_n$ - the neutral temperature in K. In our experiments, the maximum mean free path for ions is of the order of 1.3mm (at $p = 4 \text{Pa}$).

2.2.2 Plasma sheath

A sheath in general is the positive-space-charge region, which develops in the plasma near a solid surface. In our experiments, the dust particles levitate in the plasma sheath near the lower electrode. In order to have give an idea of the environment of the particles in the experiment, we explain here some main features of the plasma sheath, as well as the different types of sheaths.

2.2.2.1 Physical principle

If a solid-state body comes in contact with the plasma, the charge carriers (electrons and ions) reach its surface. Initially, the electron flux $\Gamma_e$ is many times larger than the ion flux $\Gamma_i$, as

- $m_e \ll m_i$;
- $T_e \geq T_i$.

In a stationary state, the fluxes have to be equal in order to avoid increase of the space charge. Thus, the wall gets negatively charged and repels the electrons and attracts the positive ions. A positive space charge region is created in front of the wall ($n_i \gg n_e$). This sheath region is typically a few
Debye lengths wide. As there are few electrons in the sheath to excite the gas, this region appears dark to the eye.

2.2.2.2 Types of sheaths

Dependent on the ratio between the basic plasma parameters (Debye length $\lambda_D$, mean free path $l_{mfp}$) and the radius $r$ of curvature of the solid-state object, around which the sheath develops, there are different types of sheaths. If we compare the sheath width (or roughly the Debye length) with the mean free path of the charge carriers (electrons and ions), we can divide the sheaths in two categories:

- collisional: $l_{mfp} \ll \lambda_D$;
- collisionless: $l_{mfp} \gg \lambda_D$.

From the formulae of Debye length $\lambda_D$ (eq. 2.1) and mean free path $l_{mfp}$ (eq. 2.4) it is obvious that the increase of pressure in a plasma chamber may result in a transition from a collisionless to a collisional situation.

Another classification of the sheaths is based on the comparison between the curvature radius $r$ of the solid body, which is in contact with the plasma, and the Debye length $\lambda_D$. We usually discuss two extreme cases of plasma sheath:

- thin sheath: $\lambda_D \ll r$;
- thick sheath: $\lambda_D \gg r$.

Further in this section, we will refer to the sheath, which develops at the boundary between the plasma and the walls of the set-up, as wall plasma sheath. In this case the sheath is thin(planar). The particle plasma sheath is the sheath, which develops around the surface of a dust particle immersed in the plasma.

2.2.2.3 Wall sheath thickness

So far in this section, we have assumed that roughly the sheath thickness can be estimated by the Debye length. Here a more precise estimation of the sheath thickness will be presented for the two types of sheath - collisionless and collisional.
Chapter 2

Collisionless sheath thickness - Child Law Sheath  Often for estimation of the sheath thickness the following formula is used [32]:

\[ s = \frac{\sqrt{2}}{3} \lambda_{De} \left( \frac{2V_0}{T_e} \right)^{\frac{3}{4}} \]  \hspace{0.5cm} (2.6)

where \( \lambda_{De} \) is the electron Debye length and \( V_0 \) - the sheath potential. This formula is result of the Child law. It is derived for the case of a sheath, which fulfills the following requirements:

- dc discharge,
- steady state,
- high voltage with respect to the plasma voltage \( (eV_0 \gg kT_e) \),
- collisionless sheath.

With some modifications, the Child law can be used to determine the sheath thickness in the case of RF-driven plasma. For a fixed current density and sheath voltage, Liebermann [32] finds that the RF amplitude sheath thickness \( s_m \) is larger than the Child law (dc) sheath thickness by a factor of \( \sqrt{50} / 27 = 1.36 \).

Collisional sheath thickness  At higher pressures, the mean free path for ions becomes smaller than the sheath thickness \( (l_{mfp,i} \leq s_m) \) and collisional sheaths have to be analyzed. This has been done by Lieberman [33], Godyak and Sternberg [34] and Sheridan and Goree [35]. The latter have derived a general formula for the plasma sheath. Here we will derive from this general formula an analytical solution for the sheath thickness for the particular case of constant momentum transfer cross section for collisions between ions and neutrals. The notation is different from the one in the original work [35] in order to keep consistence in the notation used in this dissertation.

\[ s = 1.155 \frac{\eta^2}{u_0 \alpha^{\frac{1}{2}}} \]  \hspace{0.5cm} (2.7)

where \( \eta = -\frac{eV_0}{kT_e} \) is the normalized wall potential, \( u_0 = \frac{u_0}{\sqrt{kT_e/m_i}} \) is the normalized ion velocity at the sheath edge, and \( \alpha = \frac{\lambda_{De}}{l_{mfp}} \) is a collision parameter. Analyzing formula 2.7, we see that the sheath thickness depends on the wall potential \( V_0 \) and on the gas pressure via the collision parameter \( \alpha \). In figure 2.2 the calculated sheath thickness is presented as function of wall potential and pressure.
2.2.2.4 Bohm criterion - Ion and electron collection in the plasma sheath

The planar sheath case has been treated in many books [32, 36]. The assumptions that are usually made in these models are:
Chapter 2

• collisionless sheath,

• quasi-neutrality at the plasma-sheath boundary, i.e. \( n_{e,sh} = n_{i,sh} \),

• Maxwellian electrons, i.e. \( n_e(x) = n_{e,sh} \exp \frac{eV(x)}{kT_e} \),

• cold ions, i.e. \( T_i = 0K \).

From the ion energy conservation (no collisions)

\[
\frac{1}{2} m_i u^2(x) = \frac{1}{2} m_i u^2_{sh} - eV(x)
\]  

and the ion flux continuity (no ionization)

\[
n_i(x) u(x) = n_{i,sh} u_{sh}
\]  

the law for the ion density in the sheath becomes:

\[
n_i = n_{i,sh} \left( 1 - \frac{2eV}{m_i u^2_{sh}} \right)^{-1/2}.
\]  

Thus, the Poisson equation

\[
\frac{d^2V}{dx^2} = \frac{e}{\varepsilon_0} (n_e - n_i)
\]  

becomes

\[
\frac{d^2V}{dx^2} = -\frac{e}{\varepsilon_0} n_{sh} \left[ \left( 1 - \frac{2eV}{m_i u^2_{i,sh}} \right)^{-1/2} - \exp \left( \frac{eV}{kT_e} \right) \right].
\]  

This equation has real solutions [5], if

\[
v_{i,sh} \geq v_B = \sqrt{\frac{kT_e}{m_i}}.
\]

This inequality is called Bohm sheath criterion. Here \( v_B \) is the so-called Bohm velocity. This criterion is giving the minimum velocity of the ions when they enter the plasma sheath.
2.2.2.5 Floating potential of the wall

If we assume \( v_{i,sh} = v_B \), the ion flux to the wall is

\[
\Gamma_i = n_{i,sh} v_b = n_{i,sh} \left( \frac{kT_e}{m_i} \right)^{1/2}.
\]  

(2.13)

The electron flux is given by [5]:

\[
\Gamma_e = \frac{1}{4} n_{e,sh} \exp \left( \frac{eV(0)}{kT_e} \right) v_{e,th} = \frac{1}{4} n_{e,sh} \sqrt{\frac{8kT_e}{\pi m_e}}.
\]  

(2.14)

At steady state these two fluxes are equal, which gives for the potential difference between the wall and the sheath edge:

\[
V(0) - V_{sh} = -\frac{1}{2} \frac{kT_e}{e} \ln \left( \frac{m_i}{2\pi m_e} \right).
\]  

(2.15)

Taking into account that there is a potential drop in the pre-sheath in order to assure a Bohm velocity of the ions at the sheath edge, i.e.

\[
V_\infty - V_{sh} = \frac{m_i v_B^2}{2e} = \frac{kT_e}{2e},
\]

the floating potential (with respect to the plasma potential) is [5]:

\[
V_f = V(0) - V_\infty = -\frac{kT_e}{2e} \left[ \ln \left( \frac{m_i}{2\pi m_e} \right) + 1 \right].
\]

This gives for argon \( V_f = -5.2 \frac{kT_e}{e} \).

2.3 Charging of dust particles in the plasma

Up to here we have discussed some theoretical aspects of general plasma physics. We will now discuss some aspects of dusty plasmas. The dusty plasma has been called also "complex" plasma as, apart from electrons, ions and neutrals, it contains an additional component - highly charged solid-state bodies. In this section, we will discuss different aspects of the charging process. We will start with a review of the known charging processes. Later we will present the problem of charging for the case of laboratory plasma and we will give the commonly used Orbit-Motion Limited theory. The charging time will be introduced and calculated for a spherical particle.
2.3.1 Review of the charging processes

A solid (dust) particle in a plasma is subject to many elementary processes (determined by the components of the plasma - electrons, ions, neutrals and radiation) leading to its charging. The charge accumulated by the particle can be both positive and negative dependent on the dominant charging process.

2.3.1.1 Charge carriers collection

As we have seen in section 2.2, a plasma is a substance, which contains charged particles - electrons and ions. If there is a solid-state particle in this environment, its surface will collect these charge carriers. If we consider a Maxwellian thermal plasma, i.e. a plasma, in which the electrons and ions have Maxwellian distributions with equal temperatures, the velocity of the electrons is higher, due to the large mass difference between ions and electrons. As a result, in the beginning of the process, the charging current of the electrons is higher and the dust particle gets charged negatively. Ions are attracted and electrons are repelled by the dust particle until the two charging currents equalize.

2.3.1.2 Secondary electron emission

The electrons and ions bombarding the dust particle can have an additional effect if they are very energetic. They can lead to the secondary electron emission by ionizing the dust particle material and ejecting electrons from it. The probability for secondary electron emission depends on the energy of the bombarding particles as well as on the secondary electron yield $\gamma$ (the average number of electrons emitted per incident ion), which in turn depends on the work function $W$ [37].

2.3.1.3 Photoemission

Another component of the plasma are the photons. The absorption of these photons by the dust particle can release electrons. They are called photo-electrons. This process also contributes to a positive charging of the dust grain. The photoelectron current depends on the energy of the incident photons, the material properties of the grain (photo-emission efficiency) and its surface potential [38]. As this effect depends strongly on the photon energy $h\nu$, the photoemission is mainly due to the UV radiation of the plasma.
2.3.1.4 Thermionic emission

Another process, which can charge the dust particle, is the thermionic emission [39]. This process is emission of electrons (or ions) from substances, which are highly heated. It can be caused by laser heating, infra-red radiation, hot filaments. In his book [6], Shukla estimates that the laser energy flux necessary to cause thermionic emission is about $300 \text{W/cm}^2$.

2.3.1.5 Others

Other processes that participate in the charging of a dust particle in a plasma are field emission (due to very high grain potential (high surface electric field) [40], radioactivity (for example, beta emission would contribute for positive charging)[40] etc. These charging processes will not be discussed in more detail, as in laboratory experiments performed at low-pressure conditions they are considered negligible.

2.3.2 Charging in the laboratory dusty plasma

2.3.2.1 Approximations

As we showed in the previous section, the problem of dust grain charging is very complex. However, discussing a usual low-pressure laboratory plasmas, we can simplify it. In this case, processes as field emission or radioactivity can be neglected. The use of lasers for illumination and observation of the dust cloud does not allow us to neglect the thermionic emission a priori without making an estimate. For example, the maximum power of the laser we use is $47 \text{mW}$ with a laser beam cross section of $4 \text{mm}^2$. As we use a beam expander in order to observe all the dust particles levitating in the plasma sheath, the effective cross section increases to at least $40 \text{mm}^2$. This gives roughly $0.1 \text{W/cm}^2$, which is insufficient for heating the dust grain, according to the estimate of Shukla [6]. Also the photo-emission and the secondary electron emission are usually neglected in the estimate of the dust charge in laboratory plasma [5]. We will also consider them negligible in our experiments.

Thus, we assume that the charge of the dust grain is determined only by the collection of electrons and ions.

2.3.2.2 Orbital-motion limited (OML) theory

The OML theory is a relatively simple and widely used theory for the charging of dust particles in plasma. It has been developed for Langmuir probes [41]. The OML theory considers a particle with radius $r_p$, which is much smaller
than the linearized Debye length $\lambda_D$, i.e. it considers a thick sheath around the particle:

$$r_p \ll \lambda_D.$$  

The electron density around the dust particle is given by the Boltzmann distribution:

$$n_e = n_\infty \exp \left[ \frac{eV(r)}{kT_e} \right]. \quad (2.16)$$

Bernstein and Rabinowitz [42] have developed the theory in the case of monoenergetic ions. Laframboise [43] has enhanced it for the case of a Maxwellian distribution function for the ions. We will assume that the ions are monoenergetic. As the dust particle is negatively charged, the ions are attracted by it. An ion would be collected, if its trajectory reaches the surface of the dust particle. It is assumed that the sheath around the dust particle is collisionless, i.e. the ions do not undergo collisions in it:

$$\lambda_D \ll l_{mfp,i}.$$  

From the conservation laws:

- conservation of energy:

$$E_0 = \frac{1}{2} m_i v_\infty^2 = \frac{1}{2} m_i v_p^2 + eV(r_p) \quad (2.17)$$

- conservation of angular momentum $\overrightarrow{L} = \overrightarrow{r} \times m \overrightarrow{v}$:

$$m_i b_{crit} v_\infty = m_i r_p v_p, \quad (2.18)$$

a critical impact parameter can be calculated:

$$b_{crit} = a \sqrt{1 - \frac{eV(r_p)}{E_0}}. \quad (2.19)$$

The cross-section for ion collection by the dust particle is defined via the critical impact parameter as follows:

$$\sigma_{coll} = \pi b_{crit}^2 = \pi r_p^2 \left[ 1 - \frac{eV(r_p)}{E_0} \right]. \quad (2.20)$$
Assuming a monoenergetic ion stream, the ion current to the dust particle will be

\[ I_i = e n_\infty v_\infty \sigma_{\text{coll}} = \pi r_p^2 n_\infty e \sqrt{\frac{2E_0}{m_i}} \left[ 1 - \frac{eV(r_p)}{E_0} \right]. \]  

(2.21)

For a Maxwellian energy distribution of the ions, the ion current has a similar form:

\[ I_i = \pi r_p^2 n_\infty e \sqrt{\frac{8kT_i}{\pi m_i}} \left[ 1 - \frac{eV(r_p)}{kT_i} \right]. \]  

(2.22)

The electron current to the dust is

\[ I_e = -\pi r_p^2 e n_e(r_p) v_{e,\text{th}} \]  

(2.23)

and in the case of Boltzmann distribution of the electron density it becomes:

\[ I_e = -\pi r_p^2 n_\infty e \sqrt{\frac{8kT_e}{\pi m_e}} \exp \left[ \frac{eV(r_p)}{kT_e} \right]. \]  

(2.24)

In steady state, the charge of the particle does not change under the influence of the ion and electron collection currents:

\[ \frac{\partial Q}{\partial t} = I_i + I_e = 0. \]  

(2.25)

The potential of the particle at steady state \( V(r_p) \) is called floating potential and is determined by the equality of the electron and ion currents to the dust particle. If we assume \( n_e = n_i \), the equation, from which we can derive the floating potential, becomes:

\[ \exp \left[ \frac{eV(r_p)}{kT_e} \right] = \sqrt{\frac{T_i m_e}{T_e m_i}} \left[ 1 - \frac{eV(r_p)}{kT_i} \right]. \]  

(2.26)

From this equation we see that the normalized floating potential \( \frac{eV(r_p)}{kT_e} \) depends only on the ratios \( \frac{T_i}{T_e} \) and \( \frac{m_i}{m_e} \).

The charge of the dust particle can be obtained from

\[ Q = 4\pi r_p^2 \sigma, \]  

(2.27)

where \( \sigma \) is the surface charge density and is related to the radial electric field \( E_r \) by

\[ \sigma = \varepsilon_0 E_r(r_p) = -\varepsilon \nabla V \big|_{r=r_p}. \]  

(2.28)

The charge of the particle becomes:

\[ Q = 4\pi \varepsilon r_p V_{r_p}. \]  

(2.29)
2.3.3 Charging time

Assuming that only the electron and ion collection currents to the dust particle are important for its charging in the plasma, the law of this process (i.e. the time evolution of the charge) will be given by:

\[
\frac{dQ_D}{dt} = I_i - I_e. \tag{2.30}
\]

As we have seen earlier, the electron current dependence on the floating potential is non-linear (see formula 2.24). Thus the charge evolution does not have an exponential behavior. A characteristic charging time \( \tau \) has been derived by Boeuf and Punset in [44]. They use the reduced potential \( y = \frac{eV(r_p)}{kT_e} \), the relation between charge and floating potential (eq. 2.29) and the expressions for the ion and electron currents from the OML theory, respectively formulae 2.21 and 2.24. Thus, the differential equation becomes:

\[
\frac{dy}{dt} = \frac{e}{4\varepsilon_0} r_p n_\infty \frac{e}{kT_e} v_{th,i} \left[ 1 + y \frac{T_e}{T_i} - \frac{v_{th,e}}{v_{th,i}} \exp(-y) \right]. \tag{2.31}
\]

At equilibrium, \( t \to \infty, \frac{dy}{dt} \to 0 \). Thus, the equilibrium reduced potential \( y_o \) is the solution of the equation

\[
1 + y \frac{T_e}{T_i} - \frac{v_{th,e}}{v_{th,i}} \exp(-y) = 0. \tag{2.32}
\]

Although the temporal evolution of \( y \) from 0 to \( y_0 \) is not exponential, the charging time has been defined as the time characterizing the potential evolution after a perturbation around the equilibrium value \( y_o \):

\[
\tau = \frac{\varepsilon}{\frac{dy}{dt}}. \tag{2.33}
\]

For the usual case of \( T_e \gg T_i \), Boeuf and Punset derive

\[
\tau = 4\varepsilon_0 \frac{\pi m_i}{e} \sqrt{\frac{kT_i}{e}} \frac{\sqrt{\frac{kT_e}{e}}}{8e \ r_p n_\infty (1 + y_0)}. \tag{2.34}
\]

Thus, the charging time is inversely proportional to the plasma density \( n_\infty \) and dust particle radius \( r_p \) and proportional to the square root of the ion temperature \( T_i \). For a particle of radius 4.9\( \mu m \) in low-temperature (\( T_i = 300K \) and \( T_e = 3eV \)) argon plasma with plasma density of \( n_\infty = 5 \times 10^{15} m^{-3} \), the charging time, following formula 2.34, is estimated to be \( 5 \times 10^{-7} s \).
2.4 Forces acting on a solid-state particle in the plasma

In capacitively-coupled radio-frequency plasmas, dust particles, which usually carry negative charge, are subject to electrostatic forces. For micrometer-sized particles in laboratory plasmas, gravity also plays an important role. In the plasma sheath, the electrostatic field results in acceleration of the ions to the electrode. These moving ions exert a force on the dust particles, called ion drag force. Usually in laboratory plasma there is a gas flow. It causes a neutral drag force. A neutral drag force is acting on a moving dust particle even if there is no gas flow. The presence of temperature gradients is exerting thermophoretic force on the particles. And finally, while illuminating the dust particles with a laser, we apply an additional force, which is called radiation pressure force. Below, we will discuss all these forces in more detail.

2.4.1 Gravity

Every dust particle in the laboratory plasma is subject to the gravitational force. For spherical particles this force is

$$\vec{F}_g = m_p \vec{g} = \frac{4}{3} \pi r_p^3 \rho \vec{g}, \quad (2.35)$$

where $m_p$ is the dust particle mass, $\vec{g}$ - the gravitational acceleration, $\rho$ - the particle density and $r_p$ - the particle radius. The gravitational force is acting downwards on the particles and it depends strongly on the particle radius (a cubic dependence).

2.4.2 Electric force

The dust particles in the plasma are charged. As discussed earlier, in an usual laboratory plasma their charge is negative. The electric force acting on such particles, in case they are small with respect to the linearized Debye length, is

$$\vec{F}_E = Q_p \vec{E}, \quad (2.36)$$

where $Q_p$ is the dust particle charge and $\vec{E}$ - the applied electric field. It is directed inwards, i.e. to the plasma glow. This is the force, which causes the trapping of the dust particles in the plasma.
2.4.3 Neutral drag force

The force due to the momentum transfer between dust particles and the neutrals in the plasma is called neutral drag force.

In a processing plasma set-up usually we have a permanent gas flow. This flow would transfer momentum to the particles in the plasma. On the other hand, the dust particles in the plasma in the common case are not in a static position and during their movement they exchange momentum with the background gas. As we will see in Chapter 3, the structure of the experimental set-up in our case allows us to neglect the first effect.

While discussing neutral drag forces, an important parameter is the Knudsen number:

\[
K_n = \frac{l_{mfp}}{r_p},
\]

(2.37)

where \(l_{mfp}\) is the mean free path of the neutrals and \(r_p\) - the particle radius.

In case of small Knudsen numbers, we have hydrodynamic regime and the neutral drag force is given by:

\[
F = 6\pi \eta r_p v,
\]

(2.38)

where \(\eta\) is the viscosity of the gas and \(v\) - the relative velocity of the particle.

In case of large Knudsen numbers, we are talking about the kinetic regime. In our experimental conditions, as the mean free path \(l_{mfp}\) is about 1.3 mm (see section 2.2.1.3) and the radius of the dust grains is \(r_p = 4.9 \mu m\), the Knudsen number is \(K_n = 260\). This is why we discuss only the kinetic case further. The momentum transfer from neutral gas particles to a dust particle is proportional to its cross section, gas particle flux and their momentum. For relatively low velocities

\[
\frac{|u_p - u_N|}{v_{th,N}} \ll 1,
\]

where \(u_p\) is the particle velocity, \(u_N\) - the directed velocity of the neutrals and \(v_{th,N}\) - the thermal velocity of the neutrals, the neutral drag force has been studied extensively by Epstein [45]. In case of specular collisions between the neutral atoms and the dust particle (i.e. the atoms' velocities after collision are normal to the particle surface) the neutral drag force is given by:

\[
\vec{F}_{ND} = -\frac{4}{3} \pi r_p^2 m_N n_N v_{th,N} (\vec{u}_p - \vec{u}_N),
\]

(2.39)

while in the case of perfect diffuse reflection, it is:

\[
\vec{F}_{ND} = -\frac{4}{3} \pi r_p^2 m_N n_N v_{th,N} (\vec{u}_p - \vec{u}_N) \left(1 + \frac{\pi}{8}\right).
\]

(2.40)
For relatively high velocities

\[ \left| \frac{u_p - u_N}{v_{th,N}} \right| \gg 1, \]

independently on the type of reflection, which is considered, the neutral drag force is given by [5]:

\[ \overrightarrow{F}_{ND} = -\pi r_p^2 m_N n_N v_{th,N} \left( \overrightarrow{u}_p - \overrightarrow{u}_N \right) \left| \overrightarrow{u}_p - \overrightarrow{u}_N \right|. \] (2.41)

The most important difference between the low and high-velocity cases is that at low velocities the force depends on the velocity and at high velocities it depends on the square of the velocity. In usual laboratory plasma the relative velocities are smaller than the thermal velocity of the neutrals. Thus, we can use the Epstein relations formulae 2.39 and 2.40.

### 2.4.4 Ion drag force

The force due to the momentum transfer between the positive ions in the plasma and the dust particles is called ion drag force. As this force is subject of many discussions lately and it plays a significant role in the explanation of some phenomena described in this thesis, we will describe it in more detail.

This force is important for the dust particle dynamics in the regions where directed ion flux is present, i.e. in the sheath regions. As the ions are positively charged and the dust particles negatively, there is Coulomb attraction between them and the interaction cross section is significantly larger than the cross section of the dust particle \( \pi r_p^2 \).

This force has two components:

- **collection ion drag force** \( F_{i,coll}^{drag} \) - due to the momentum transfer from the ion to the dust particle when the ion is collected, i.e. reaches the dust particle surface;

- **orbit ion drag force** \( F_{i,orb}^{drag} \) - due to the momentum transfer to the dust particle from a positive ion, deflected in its electrostatic potential field.

The collection cross section \( \sigma_{coll} \) has been derived for mono-energetic ions in [44]. It depends on the cross section of the dust particle, its floating potential and the ion energy:

\[ \sigma_{coll} = \pi b_{coll}^2 = \pi r_p^2 \left[ 1 - \frac{2eV(r_p)}{m_i u_i^2} \right]. \] (2.42)

Thus the collection ion drag force will be:
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\[ F_{i,\text{drag}}^{\text{coll}} = n_i m_i u_i \overrightarrow{u_i} \pi r_p^2 \left[ 1 - \frac{2eV(r_p)}{m_i u_i^2} \right]. \]  

(2.43)

An approximate formula for the collection drag force in case of a more general ion distribution function has been given by Barnes et al. [46] by replacing the directed velocity by the "total" velocity, corresponding to the ion total mean energy:

\[ u_i \rightarrow v_i, \text{tot} = \sqrt{u_i^2 + v_{i,\text{th}}^2} = \sqrt{u_i^2 + \frac{8kT_i}{\pi m_i}}. \]

(2.4.3)

If we assume the cut-off Coulomb potential distribution (i.e. Coulomb potential, if \( r < \lambda_D \), 0 if \( r > \lambda_D \)), the momentum cross section for the orbit ion drag force is given by:

\[ \sigma_{\text{orb}} = 4\pi \int_{b_{\text{coll}}}^{\lambda_D} \frac{2pdP}{1 + \left( \frac{p}{b_{\pi/2}} \right)^2}, \]

(2.4.4)

where \( P \) is the impact parameter and \( b_{\pi/2} = r_p \frac{-eV(r_p)}{m_i u_i^2} \) is the asymptotic parameter, for which the angle is \( \frac{\pi}{2} \) [36]. This approximation is reasonable for \( r_p \ll \lambda_D \).

This gives the following expression for the orbit cross section:

\[ \sigma_{\text{orb}} = 4\pi b_{\pi/2}^2 \ln \left( \frac{\lambda_D^2 + b_{\pi/2}^2}{b_{\text{coll}}^2 + b_{\pi/2}^2} \right) \]

(2.4.5)

For non-monoenergetic ions Barnes et al. [46] have introduced the following approximate formula:

\[ \overrightarrow{F}_{i,\text{orb}} = n_i m_i \sigma_{\text{orb}} v_{i,\text{tot}} \overrightarrow{u_i}. \]

(2.4.6)

Kilgore et al. [47] have given a different expression for the orbital ion drag force in case of monoenergetic ions and cut-off Coulomb potential:

\[ \overrightarrow{F}_{i,\text{orb}} = 2\pi b_{\pi/2}^2 \ln \left( 1 + \frac{\lambda_D^2}{b_{\pi/2}^2} \right) n_i m_i u_i \overrightarrow{u_i}. \]

(2.4.7)

Kilgore et al. [47] have performed numerical calculations of the momentum-transfer cross sections between mono-energetic positive ions and dust particles for:

- a particle sheath potential profile obtained using self-consistent Poisson-Vlassov theory,
• an attractive screened Coulomb potential:

\[ U(r) \sim \frac{\exp \left( -\frac{r}{\lambda_D} \right)}{r}, \]

• the already discussed cut-off Coulomb potential.

They have shown that the cut-off Coulomb potential underestimates the orbit momentum-transfer cross section.

Lately Khrapak et al. [48] have introduced analytical formula, which represents better the momentum-transfer cross section between positive ions and dust particles. In the commonly used formula 2.45 for this cross section, it is assumed that the upper boundary of the integral is \( \lambda_D \). In reality, as the dust grain charge in the plasma is very large, the Coulomb ion-dust interaction has longer range than the Debye length. The proposal of Khrapak et al. [48] is to use a larger upper limit for the integral in the formula for the orbital cross section eq. 2.45 and that the new upper limit is simply defined by:

\[ r_0(p_{\text{max}}) = \lambda_D, \]

where \( r_0 \) is the distance of closest approach of the ion to the dust grain during collision. The solution of this equation is found to be:

\[ p_{\text{max}} = \lambda_D \sqrt{1 + \frac{2b_{\pi/2}}{\lambda_D}}. \]

Thus, the orbit momentum transfer cross section becomes:

\[ \sigma_{\text{orb}} = 4\pi b_{\pi/2}^2 \ln \left( \frac{\lambda_D + b_{\pi/2}}{r_p + b_{\pi/2}} \right). \quad (2.48) \]

Note that all the formulae for the ion drag force above are derived assuming the Debye length \( \lambda_D \) to be larger than the particle radius \( r_p \). In our case, \( \lambda_D = 0.02 \text{mm} \) and usually \( r_p = 4.9 \mu\text{m} \). Thus the above formulae are valid.

### 2.4.5 Thermophoretic force

If there is a gradient of the neutral gas temperature in the reactor, there will be a different momentum transfer by the neutrals on the different sides of a dust particle. The thermal velocity of the neutrals on the warmer side is larger than this of the neutrals on the colder side. Thus, the momentum
transfer rate is larger on the warmer side of the dust particle. This leads to a resultant net force, pushing the dust particle to the colder place in the reactor. This force is called thermophoretic force. Jellum and Graves [49, 50] have observed thermophoresis effects in radio frequency glow discharge. An analytical expression for the thermophoretic force has been given by Talbot et al. [51]:

\[
F_{th} = -\frac{32}{15} \frac{r_p^2}{v_{th,N}} \left[ 1 + \frac{5\pi}{32} (1 - \alpha) \right] k_T \nabla T_N,
\]

(2.49)

where \( r_p \) is the particle radius, \( v_{th,N} \) - the thermal velocity of the neutrals, \( k_T \) is the thermal conductivity of the gas, \( T_N \) is the neutral gas temperature and \( \alpha \) - an accommodation coefficient. It is assumed that \( \alpha \approx 1 \) for dust surface temperature \( T_{dust,\text{surface}} \) and gas temperature \( T_g < 500K \) [51].

### 2.4.6 Radiation pressure force

Radiation pressure is the momentum transferred by photons to the surface per unit area per unit time. In general, for a laser beam with intensity \( I_{laser} \), the radiation pressure force \( F_{laser} \) is given by [52]:

\[
F_{laser} = q n_1 \pi r_p^2 \frac{I_{laser}}{c},
\]

(2.50)

where \( n_1 \) is the refractive index of the medium around the particle, \( c \) is the speed of light and \( q \) is a dimensionless factor, determined by the reflection, transmission and absorption of photons on the particle and independent of the particle size and laser intensity[52].

### 2.4.7 Order of magnitude of the forces acting on a particle in the plasma

After discussing the different forces acting on a dust particle in the plasma sheath, in this section we will estimate the order of magnitude of these forces for typical conditions of a capacitively-coupled radio-frequency plasma. The results of these calculations are given in table 2.2.

For the calculations given in table 2.2 we have assumed the argon plasma to be at a pressure of 20Pa (which results in \( n_{\text{neutral}} = 4.8 \times 10^{21} m^{-3} \), assuming ideal gas), with a plasma density of \( 5 \times 10^{15} m^{-3} \). The electron temperature is considered 3eV and the ion and neutral temperature - 300K, thus the difference between them is 2 orders of magnitude. The calculations are performed for a melamine formaldehyde (\( \rho = 1514 \frac{kg}{m^3} \)) particle with a radius
Table 2.2: Forces acting on a dust particle in the plasma sheath: used formulae and calculated values

of \( r_p = 4.9 \times 10^{-6} \text{m} \). In calculating the neutral drag force we assume a static gas and a particle moving with a speed of 16mm/s. The ion drag force is assumed equal to the orbit ion drag force as our calculations show that the collection ion drag force is one order of magnitude smaller. It is calculated, using equation 2.47 and assuming the ions having the Bohm velocity. As the ions are accelerated in the sheath, the assumption of Bohm velocity for the ions leads to a lower estimate of the actual ion drag force acting on the particles levitating in the sheath. For the thermophoretic force, we assume a temperature gradient of 2K/cm. The results from the simulation of Akdim and Goedheer [53] show that this is a reasonable assumption. In calculating the radiation pressure force, we assume that the plasma has a refractive index \( n_1 = 1 \), i.e. as vacuum, the laser intensity is roughly estimated as the laser power (47mW) going through the visible cross section of the laser beam. The dimensionless coefficient \( q \), which is determined by the reflection, transmission and absorption of photons by the particles, is taken from [52].

The estimate of the forces, presented in table 2.2, gives an idea about their importance in the sheath. In the rest of this thesis the radiation pressure force will be neglected. The main focus will be on the gravitational, electrostatic and ion drag forces.

### 2.5 Characteristics of the collective behavior of particle cloud

In the previous sections we have discussed the charging processes and the forces acting on a single particle in the plasma. Often we do not deal with one isolated dust particle, but with clouds of particles immersed in the plasma.
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At some conditions the cloud can exhibit collective behavior. Ikezi [13] introduced the so-called Coulomb coupling parameter $\Gamma$. This parameter represents the ratio of the electrostatic interaction energy to the particle kinetic energy. Assuming a screened Coulomb potential, the electrostatic interaction energy is:

$$E_{\text{coulomb}} = \frac{Q^2}{4\pi\varepsilon_0 a} \exp\left(-\frac{a}{\lambda_D}\right),$$

where $a$ is the inter-particle distance.

The dust thermal energy is:

$$kT_D = \langle m_D \frac{v_D^2}{2} \rangle.$$  \hspace{1cm} (2.51)

Thus the Coulomb coupling parameter is given by:

$$\Gamma = \frac{Q^2}{4\pi\varepsilon_0 a kT_D} \exp\left(-\frac{a}{\lambda_D}\right).$$  \hspace{1cm} (2.52)

Based on this parameter the dusty plasma can be:

- weakly coupled: $\Gamma \ll 1$;
- strongly coupled: $\Gamma \gg 1$.

It is considered that at $\Gamma \gg 2$ we have a Coulomb liquid and at $\Gamma \gg 170$ - a Coulomb crystal. In our experiments, at different plasma parameters (pressure, power), we have observed strongly coupled dusty plasmas (Coulomb crystals) as well as weakly coupled ones.
Chapter 3

Experimental set-up

3.1 Introduction

The experiments presented in this dissertation have been performed in a low-pressure capacitively-coupled radio-frequency plasma, which is commonly used in the dusty plasma research all over the world.

In this chapter, the different parts of the experimental set-up are described. As the work, presented here, is performed in a low-pressure plasma, we start with the description of the vacuum and gas system. This is done in section 3.2. Section 3.3 gives information on the plasma generation and the electrode configuration used to trap the dust particles. In section 3.4, the particle injection is described, as well as the type of particles used in the experiment. Section 3.5 deals with the illumination and detection of the particles. Furthermore, we will give some information on the Langmuir probe, which is used for an estimate of the potential profile in Chapter 4. Plasma parameters measured via this technique are given. In the final section 3.7 the Plasma Impedance Monitor (PIM), used for a more precise description of the electrical parameters of the plasma, is described.

3.2 Vacuum and gas handling

The plasma reactor consists of a chamber with circular flanges in every wall for the connection of the electrode (on the bottom), the particle injector and the diagnostics. A picture of the experimental set-up is presented in figure 3.1.

As the experiments are performed in a low-pressure plasma, first we need to create vacuum and to supply the set-up with the working gas. A scheme of the vacuum and gas system is shown in figure 3.2. The reactor is connected to
a pumping system, providing a background pressure of 0.1 Pa. The pumping system consists of two pumps. Between the pumping system and the reactor there is a manually actuated valve, via which we can control the pumping speed. The primary pump (Rotary vane pump: Pfeiffer Vacuum Duo 016) is used to reach pressures, at which the second (roots) pump of Emod Motoren GmBH is able to start. The switching on of the second pump is automated and happens when the pressure measured by a Balzers Compact Pirani gauge reaches 2 mbar.
The set-up is equipped with a gas bottle of argon (Ar). The Ar gas flow is controlled by a Brooks 5850E series mass-flow controller. In all the experiments the flow was 10sccm or lower. The pressure has been measured using a MKS Baratron membrane gauge (MKS Instruments Deutschland GmbH), which is gas independent and works in the range of 0 to 1Torr (0 to 133Pa). Further in this dissertation, the pressure will be given in Pa. The range of pressures, in which the experiments have been performed, is 4 to 40Pa.

The vacuum port and the gas inlet are positioned at the top of the set-up at a distance of 15cm above the bottom electrode. This configuration and the low gas flows are chosen in order to avoid possible disturbance of the dust cloud by the gas flow. Effectively, there is no gas flow in the region where the particles are trapped.
3.3 Plasma generation. Electrode configuration

After filling the reactor with argon at the desired pressure, a capacitively-coupled plasma is created (see figure 3.3). In figure 3.4, a scheme of the plasma generation is presented. In the bottom of the vessel, a powered electrode is positioned. It is connected to a radio-frequency function generator Agilent 33250A via an impedance matching network. The generator is providing a sinusoidal $13.56 \text{MHz}$ frequency. The power is amplified by a RF amplifier (model 75A250 of Amplifier Research). In the power line, a power-meter (Bird) is connected before the matching network. With this power meter we can measure both the forward and reflected power. Via the matching network we minimize the reflected power and provide maximum power going into the plasma. In this dissertation, by power we mean the difference between the forward and reflected power, measured before the matching network. So losses in the lines to the plasma and in the matching network are not subtracted. The range of powers used in the experiments, presented in this thesis, is 3 to 70\text{W}.
The powered electrode has a diameter of 10cm. It is water-cooled. On top of the powered electrode, an aluminum disk with a depression in the middle is installed. The depression is used to create a potential well for successful trapping of the dust particles. The depression can have different forms. In the experiments presented in this thesis we have used circular depressions. In most of the experiments, the depression is 3cm in diameter and 3mm deep. To be able to investigate the trap dependence of some of the phenomena, we have made series of measurements with different size circular depressions - smaller (d = 1cm) or bigger (d = 5cm) in some of the experiments.

The walls of the chamber serve as grounded electrode. The isolation between the powered electrode and the grounded bottom of the chamber is of Teflon. The different sizes of the powered and grounded electrodes result in a bias voltage (negative with respect to the ground).

### 3.4 Particles and particle injection

In the plasma, we inject the objects of investigation. In the experiments, presented in chapters 4, 5 and 6, we use Melamine Formaldehyde particles, produced by SPECHT GmbH, Berlin. A picture of these particles is shown in figure 3.5. Melamine formaldehyde is a polymer used often in moulding.
The particles we use usually have a diameter of $9.78\mu m$. In the field of dusty plasmas, these are considered large particles. In normal laboratory conditions, they are trapped in the sheath of the plasma close to the lower powered electrode.

![Figure 3.5: Microscope picture of Melamine formaldehyde particles with diameter of 9.78µm](image)

The particles are placed in a container, at the end of a manipulating arm. The arm is horizontally translatable. The bottom of the container is a sieve with a mesh of circular holes (Stork Veco B. V.). The size of the holes has to be several times bigger than the diameter of the particles [54]. We move the arm to the middle of the vessel and then we mechanically inject the particles. The number of trapped particles in different experimental series varies from one to more than 400, depending on the mesh and the strength of the vibrational insertion.

We inject the particles in the plasma at higher power and pressure, because in these conditions the trapping is more efficient.

### 3.5 Illumination and detection

The particles injected and trapped above the center of the depression are illuminated with a laser. In some of the experiments, an argon ion laser ($488\,nm$) has been used, in others - a diode laser ($660−663\,nm$). The light coming from the laser passes through a beam expander (a system of 4 different prisms or a
The resultant beam has a horizontally elongated form. The width of the laser sheet is more than 2 cm at the distance, at which the cloud of particles is levitating. This allows the whole cloud to be illuminated. On the side and on the top of the chamber, there are monochrome CCD (charge coupled device) video cameras. The cameras have Macro-lenses (Sigma 70-300 mm, F4-5.6 DL). One of the cameras operates at 25 frames/s. Its signal is recorded on a S-VHS video-recorder. The movies from the experiments are digitized via a frame grabber Pinnacle DV500 and video editor Adobe Premiere 5.1. The second camera Pulnix is a newer generation camera and works at 60 frames/s. It is directly connected to a computer and its action is programmed via MIL-Lite software.

3.6 Langmuir probe

Langmuir probes are one of the oldest plasma diagnostics tools. It is widely used for characterization of the electrical parameters of plasmas. In order to characterize the plasma, in which we have performed the dusty plasma experiments, an automated Langmuir probe of Scientific Systems SMART-PROBE is used. This probe system is designed to measure:

- plasma floating potential \( V_f \),
- plasma potential \( V_p \),
- electron temperature \( kT_e \),

Figure 3.6: Scheme of the illumination and detection system.
Chapter 3

• electron number density $n_e$,

• ion number density $n_i$,

• electron energy distribution function.

The Langmuir probe has been connected to one of the side flanges of the set-up. The probe tip is made of tungsten and has originally a length of 10\textit{mm} and a radius of 0.19\textit{mm}. As our main idea was to perform scanning measurement of the plasma parameters in the radial direction, we reduced the tip length to 5\textit{mm} in order to reduce the overlapping of the measurements. The body of the probe itself has a diameter of 8\textit{mm}.

The probe is equipped with an Auto Linear Drive (ALD) Unit. It allows the probe to move in a range of 25\textit{cm} with steps of 0.1\textit{cm}. The measurements of the plasma parameters have been performed in the region above the center of the 10\textit{cm}-diameter powered electrode. The measurements have been performed in a range of 4\textit{cm} above the center of the electrode.

The Langmuir probe is equipped with a data acquisition system connected to a personal computer. Before every measurement, the probe is cleaned by applying a large negative pulsed voltage.

![Typical Langmuir probe I-V characteristic.](image)

Figure 3.7: Typical Langmuir probe I-V characteristic.
As this dissertation is dedicated to investigation of different phenomena, which develop in dusty plasma containing micrometer-sized particles, our interest is mainly in the parameters of the plasma sheath. Unfortunately, as it is well known, the Langmuir probe theory fails in the sheath. Nevertheless, it can give qualitative information close to the structured electrode. Data on the sheath profile will be presented in Chapter 4.

In figure 3.7 a typical measured I-V characteristic is presented. The measurement is performed in the plasma glow at a pressure of 16 Pa and a power of 10 W at a distance of 2 cm above the electrode, which is well above the sheath region (see figure 2.2). The plasma parameters estimated by the SmartProbe software are given in table 3.1.

<table>
<thead>
<tr>
<th>plasma parameter</th>
<th>measured value</th>
</tr>
</thead>
<tbody>
<tr>
<td>floating potential</td>
<td>18.3 V</td>
</tr>
<tr>
<td>plasma potential</td>
<td>28.7 V</td>
</tr>
<tr>
<td>electron temperature</td>
<td>2.7 eV</td>
</tr>
<tr>
<td>electron density</td>
<td>$7 \times 10^9 \text{cm}^{-3}$</td>
</tr>
<tr>
<td>ion density</td>
<td>$5.6 \times 10^9 \text{cm}^{-3}$</td>
</tr>
</tbody>
</table>

Table 3.1: Plasma parameters measured with SmartProbe in the plasma at a pressure of 16 Pa and a power of 10 W

### 3.7 Plasma Impedance Monitor

In order to better characterize the plasma electrically, a Plasma Impedance Monitor of Scientific Systems - SmartPIM™ has been used. The Plasma Impedance Monitor is placed in the RF line and simultaneously captures and displays the RF current, the RF voltage and the phase shift between voltage and current of the fundamental and the first four harmonics of the radio-frequency signal, which drives the plasma. Apart from this, the power deposited into the plasma and the impedance of the plasma are derived from the above-mentioned measurements.

In general, the SmartPIM system consists of a sensor head, an acquisition and control unit and a PC. The sensor head is connected immediately in front of the powered electrode, i.e., after the matching network (see figure 3.4).

In all the measurements presented in this thesis the power applied to the electrode has been measured via a Bird power meter. In order to have more precise values of the power deposited in the plasma, calibration of the power measured via the power meter to the power derived by the PIM is performed. The results are given in figure 3.8. As the PIM is connected in the power line...
between the matching network and the electrode, it gives a more precise value for the power dissipated in the plasma. The Bird powermeter is connected in front of the matching network and does not account for the power dissipated in it. The data presented in figure 3.8 suggest that the power measured using the Bird powermeter is systematically about 25% higher than the power, measured by the PIM.

![Figure 3.8: The power derived by the PIM as a function of the power measured by the Bird power meter for 3 different pressures.](image)

Another important parameter characterizing the plasma is the potential of the electrode. In figure 3.9 the potential of the electrode as measured by the PIM is given as a function of the power measured by the power-meter.

All the experiments discussed in the next chapters have been performed in the experimental set-up described here. The small modifications necessary for the experiments on counter-phase oscillations are discussed in section 6.3 of Chapter 6.
Figure 3.9: The electrode potential as a function of the power measured by the Bird power meter for 3 different pressures.
Chapter 4

Sheath voids in a cloud of spherical dust particles

Parts of this chapter have been published as:
"Evolution of a dust void in a radio-frequency plasma sheath"
R.P. Dahiya, G.V. Paeva, W.W. Stoffels, G.M.W. Kroesen,
K. Avinash and A. Bhattacharjee

4.1 Introduction

In this chapter results from an investigation on the sheath void phenomenon are presented. The term "void" defines a dust-free region in the dust cloud levitating in the plasma.

In 1996, Praburam and Goree first introduced the term "void". They first observed the new phenomenon of dust-free region in the middle of the bulk plasma. They called it "great void" [23]. In their work, the dust particles were nanometer-sized and were grown in-situ by sputtering graphite electrodes. The formation of the void was preceded by a sudden onset of a filamentary mode. This work was continued by Samsonov and Goree [24].

In 1999, voids were again observed by Morfill et al. [25]. Their experiment was performed with micrometer-sized dust particles under micro-gravity conditions. The void was again observed in the bulk plasma. Its formation appeared to occur without an initial turbulent phase.

In all the above-mentioned experiments where a void is observed [23–25], the void size is increasing with the RF power. A necessary condition for void formation in these experiments is that the dust particles are above a critical size.
Various mechanisms have been proposed to explain the dynamical process of void formation. These include mainly

- the thermophoretic force due to temperature gradients [55]
- the ion drag on dust particles [24, 56–59].

A number of theoretical calculations have considered the role of the ionization instability [60–62] in the presence of ion drag and collisions of ions and dust with the background neutral gas as a possible dynamical trigger for void formation.

In this chapter, we will present a systematical investigation of the evolution and dynamics of voids in dust clouds suspended in a RF plasma sheath. For the first time, similar observations have been reported in 1993 by Dalvie et al. [26]. In their experiment, dust particles were levitating above a 22mm × 6mm groove in the bottom electrode. At low pressure, the particles formed a line. While increasing the pressure, the particles formed "two distinctly separated lines inside the groove".

Our aim is to investigate the structuring of the dust cloud (void formation) in the sheath in order to propose a working mechanism, which can explain this behavior. In section 4.2, we investigate the variation of the void size with various control parameters, such as input RF power and neutral gas pressure in argon. In section 4.3, Langmuir probe measurements of the sheath profile are performed.

In section 4.4, two theories dealing with the modelling of the cloud size are presented. In subsection 4.4.1 we present a simple phenomenological model based on the dynamic balance of a repulsive Yukawa force with cohesive forces that may be present between the grains. This model easily gives the observed dependence of the inter-particle distance on pressure and power. In subsection 4.4.2, a surface tension theory triggered by this experiment is briefly explained.

Further, in section 4.5, a two-dimensional fluid model of our plasma set-up, build by the group of W. Goedheer at FOM-Rijnhuizen, is presented. The results of this model do not reproduce the experimental results. In section 4.6, another model, build in the group of M. Kushner at the University of Illinois, is presented. This model does reproduce the experimental observations. In the following section 4.7, a comparison between these two models is made in order to identify the differences that result in void formation in the second model.
4.2 Voids in an argon plasma - experimental results

In this section we will present the experimental data on sheath void formation in clouds of melamine formaldehyde particles of diameter 9.8µm suspended in an argon plasma above a circular trapping depression in the electrode.

Figure 4.1: Series of top-view pictures of the cloud trapped above a 3cm circular depression in the powered electrode, showing the void formation with increasing power. The outer light ring is the edge of the circular depression in the electrode.
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In order to visualize the phenomenon, in figure 4.1 a series of top-view pictures of the dust cloud with increasing power is presented. The power increases from (a) to (f). At low power the cloud has a circular form. While increasing the power, the particles from the center of the cloud start moving aside and this results in the formation of a void in the middle of the cloud. Further in this section, we will discuss the dependence of this specific structure of the dust cloud on gas pressure, RF power, as well as on the trap size.

4.2.1 Power dependence

In this subsection, the power dependence of the observed void formation is analyzed in more detail. In figure 4.2 a typical graph of the cloud and void diameter dependence on the applied RF power is given. In this particular case the gas pressure is $19.5\text{ Pa}$. We evaluate the outer diameter of the dust cloud and the void diameter from a series of video images similar to the ones in figure 4.1.

![Figure 4.2: Power dependence of the cloud and void size at pressure of $p_g = 19.5\text{ Pa}$. The trapping depression is 3cm in diameter.](image)

An interesting detail in this figure is the initial decrease of the diameter of the dust cloud. At low powers up to $10W$, the cloud shrinks slightly. Above this power, the cloud starts expanding. Above a threshold power of $25W$, a void forms in the center of the cloud. Above $25W$ there is a fast formation
Sheath voids in a cloud of spherical dust particles

Figure 4.3: Power dependence of the surface of the monolayer cloud at a pressure \( p_g = 19.5 P_a \), corresponding to figure 4.2.

Figure 4.4: Particles height above the electrode as function of the applied RF power of dust free space in the middle of the cloud. At the same time the increase in the cloud diameter slows down and reaches saturation at about 50W.
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In figure 4.3, the visible cloud area is given as a function of power. This graph is giving indirect measure of the inter-particle distance.

After void formation the cloud surface decreases by more that one order of magnitude. Thus, we conclude that the inter-particle distance in the cloud decreases while the void is formed.

In figure 4.4 the particle height as function of power is given. The height is measured with respect to the bottom of the depression, above which the particles are trapped. As the depression is 3mm deep, the y-axis of the graph is intersected at level of 3mm. From the graph we can see that the particles move farther from the electrode with increasing power.

4.2.2 Pressure dependence

![Figure 4.5: Pressure dependence of the cloud and void size at a power $P_{RF} = 10W$. The trapping depression is 3cm](image)

Similar to the power dependence of the void formation, we have also investigated the pressure dependence of the void formation. The cloud and void diameters as a function of the background pressure $p_g$ for argon flow of 10sccm and RF power of 10W are shown in figure 4.5. The experimentally measured outer diameter of the dust cloud continuously increases from 4.5mm at $p_g = 10.7Pa$ to 7.9mm at $p_g = 19.5Pa$, where the void sets in. Initially, the void expands rapidly with pressure till $p_g = 23Pa$ and then its
Sheath voids in a cloud of spherical dust particles

Figure 4.6: Pressure dependence of the cloud surface at a power $P_{RF} = 10W$. The trapping depression is 3cm

growth slows down. It is obvious from the fact that the cloud and void diameters approach each other that the width of the ring containing the particles shrinks at higher pressures. At higher pressures beyond 28Pa the particles are observed to align in circular rings in-between void diameter and the outer diameter of the cloud.

In figure 4.6 the dependence of the cloud surface on the pressure is given. Comparing figures 4.5 and 4.6 we can see that in the pressure range, in which the cloud appears compact, the cloud surface increases as its diameter increases. After the void formation threshold, there is a small range of pressures (in our measurements represented by the data point at 19.5Pa), in which the cloud surface still increases, even though the void radius increases faster than the one of the cloud. Above this transition range, the cloud surface steadily decreases.

In figure 4.7, the height of the dust particles in the sheath as a function of gas pressure is presented. The measurement of the height is done from the level of the electrode trapping depression with depth of 3mm. The height of the dust particle decreases with increasing pressure. This can be expected, considering the sheath thickness decreases with pressure (see figure 2.2 in Chapter 2).
4.2.3 Trap diameter effect on the cloud behavior

After establishing that the void in the sheath cloud changes with pressure and power, we have investigated the effect of the size of the trap, in particular its diameter, on the void. We have performed a pressure and power dependence investigation of the cloud for 3 different trap diameters - 1cm, 3cm and 5cm. Note that initially the sheath void formation has been observed in the case of a 3cm-diameter trap.

In figure 4.8 we show a side view picture of dust cloud trapped above the 1cm trapping depression. The picture is reconstruction of several pictures, as the height of the cloud is larger than the laser sheet thickness. In the case of 1cm-diameter trap, we did not observe void formation.

While applying the 5cm-diameter depression in the electrode, the trapping appeared not efficient and the particles did not form a cloud with clear contours.

The trapping depression appears to have an important role not only on the trapping itself but also on the structuring of the cloud levitated above it. It is quite possible that the void formation appears only at a certain ratio between the trap diameter and its depth. This problem has not been
4.3 Langmuir probe measurements of the sheath profile

In the discussions on voids observed in bulk plasmas, two forces have been considered to cause the phenomenon - thermophoretic and ion drag force. We also have considered both forces. The ion drag force has an electrical background, which is not the case for the thermophoretic force. As we have mentioned in Chapter 3, we have performed Langmuir probe measurements in order to obtain information on the structure of the electrical potential trap above the depression in the electrode, used to confine the dust particles.

We are interested in the parameters of the plasma sheath at the level of levitation of the dust particles. Unfortunately, the Langmuir probe theory is not valid in the plasma sheath. Therefore we have performed the measurements at a distance of 1.5cm above the electrode for different plasma parameters. As we see from figure 2.2 in Chapter 2, the distance of 1.5cm above the electrode should correspond to the pre-sheath or bulk plasma. In order to achieve this distance to the electrode, the electrode has been elevated. This
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way we reduce the distance between the electrode and the fixed axis of the Langmuir probe. It is assumed that the decrease in the distance between the powered and grounded electrode does not affect the plasma parameters, as this distance is much larger than the thickness of the introduced plate. Here we present the data for the floating potential, as they are measured directly from the I-V characteristic without applying any theory.

The results of the measurements of the floating potential at different pressures are shown in figure 4.9. Note that this is the floating potential with respect to the ground. The measurements are performed above the 3cm-diameter depression in the electrode. It can be clearly seen that with increasing pressure in the chamber, the potential profile gets flatter and at 33Pa a dip in the profile is observable.

Figure 4.9: Floating potential with respect to the ground, measured at 1.5cm above the electrode at different pressures. The measurements are performed above the 3cm-diameter depression in the electrode. Position 0 corresponds to its center.

4.4 Cloud volume modelling

4.4.1 Phenomenological (thermodynamic) model

In this section we will present a simple phenomenological theory, based on the balance between the repulsive screened Coulomb (Yukawa) force between
the charged dust particles and "cohesive" forces that may be present between them. Using this model, the volume of the particle cloud as a function of the external parameters can be determined. The calculations appear to be in good agreement with the experimental observations. The model does not concentrate on the reason for the formation of the void but on the dust cloud volume and its dependence on the parameters. Morfill et al. [25] suggested the thermophoretic force as a mechanism leading to dust cloud compression. The presence of a radial potential trap in our electrode configuration can also facilitate the formation of a void. The depression in the electrode induces a curvature in the sheath in the radial direction. On its turn, it deflects the positive ions. Thus the positive ions acquire a radial velocity component. This causes a radial ion drag force pushing the particles towards the edges of the circular trap. Here, we propose a simple formalism, which takes into account the balance between the repulsive Yukawa force and cohesive forces. Note that the theory is based on force balance in a stationary state, so the energy minimization principle can be applied even though the sheath is a thermodynamically open system.

The particular cohesive force used further in this section is the Van-der-Waals-like mean field, which can be derived from the well-known principles of statistical thermodynamics applied to strongly coupled Yukawa systems [63]. This attractive force is due to the potential energy of the background plasma, which on average neutralizes the charge of the dust particles.

We do not suggest that the Van-der-Waals-like mean field force is the one relevant for our experiment, but rather use it as a proxy for other cohesive forces (e.g. pairwise thermophoretic force or ion shadowing force [64] induced by the ion wakefield [65]). The proposed phenomenological approach allows to predict the trend in the behavior of the dust cloud volume.

For a dusty plasma, the normalized potential energy per particle due to the cohesive field above can be expressed as [66]:

\[
W_1 = -\frac{3}{2} \frac{\Gamma_A}{\kappa^3}, \tag{4.1}
\]

where \(\kappa = a/\lambda_D\) is the ratio between the inter-particle distance and the Debye length, and \(\Gamma_A\) is parameter connected to the coupling parameter \(\Gamma\), introduced with equation 2.52, via

\[
\Gamma_A = \kappa \Gamma.
\]

The potential energy per particle due to the Yukawa field is given by:

\[
W_2 = k \Gamma_A \frac{\exp(-\kappa)}{\kappa}, \tag{4.2}
\]
where \( k \) is the number of near neighbors. The particles try to attain a configuration with minimum potential energy. Thus, the inter-particle distance establishes at a value \( a_m = \kappa_m \lambda_D \), where \( \kappa_m \) is obtained by minimizing the potential energy \( W = W_1 + W_2 \) with respect to \( \kappa \). Respectively, the optimum volume of a cloud consisting of \( N \) particles is

\[
V_m = N \frac{4}{3} \pi (\kappa_m \lambda_D)^3. \tag{4.3}
\]

We can compare it to the volume available to the particles \( V = \pi r_c^2 h \), where \( r_c \) is the cloud radius and \( h \) - the cloud thickness. From the experiments we have seen that \( r_c \) increases with pressure and power (via the external confining potential). On the other hand, the plasma density is scaling approximately linearly with the gas pressure and the RF power [67, 68] in our experimental conditions. Thus the Debye length (see eq. 2.1 in Chapter 2) and consequently the optimal volume \( V_m \) (via eq. 4.3) vary inversely with these parameters.

At low pressure or power, we have \( V_m > V \). Increasing the pressure and power, \( V \) increases (see figures 4.2 and 4.5) and \( V_m \) decreases. For large values of pressure and power \( V > V_m \). The model predicts only the volume of the cloud but not its shape in the state of minimum potential energy. The transition to the state of \( V > V_m \) can be expressed in shrinking of the cloud or formation of a void. The exact reason for the preference of the second situation is not treated within this model but will be discussed further in this chapter (see section 4.7). Here we assume that at large power and pressure a void of volume \( V_{\text{void}} = V - V_m \) is developed. The condition \( V = V_m \) defines a threshold for the void formation. Firstly, we normalize \( V_m \) on one of the experimental points and then, the void diameter is calculated as a function of the external cloud diameter, the pressure and the power.

In figure 4.10 the fits of the void diameter as a function of power and pressure for the experimental data from figures 4.2 and 4.5 are presented. The normalization has been performed on the last data point in the corresponding graph. The model prediction of the void diameter trend, represented by the solid line, matches quite well the measurements. The threshold for void formation as a function of pressure corresponds to the experimental findings, but as a function of power it gives a lower value. This can be due partially to the way of determining the void diameter in the experiment, as in the range of \( 20 - 25W \) some rarefaction is observed, but the void has been assumed not developed as no clear contours have been observed.
Figure 4.10: The theoretical fit of the void diameter based on the thermodynamical approach for the (a) power and (b) pressure dependence.

4.4.2 Surface tension theory

Here we will present briefly a theory, developed by Ignatov, Schram and Trigger [69, 70] and triggered by the results of our experiments. A schematic
representation of the model is given in figure 4.11. This theory is based on the Child-Langmuir equation, commonly used for high-voltage collisionless sheaths (see section 2.2.2.3). The dust layer is considered as a rigid thin charged sheet positioned at height $z_d$ and perpendicular to the ion flow.

![Figure 4.11: Schematic representation of the surface theory model. The electrode is positioned at $z_0$, the sheath edge at $z_{sh}$ and the dust layer at $z_d$. The potential of the electrode is $-V$ with respect to the plasma potential and the potential of the sheath edge is considered 0. After Ignatov [69]](image)

The boundary conditions used to solve the Child-Langmuir equation are:

$$\varphi(z_{sh}) = 0, \varphi'(z_{sh}) = 0, \varphi(z_0) = -V,$$
$$\varphi(z_d + 0) - \varphi(z_d - 0) = 0, \varphi'(z_d + 0) - \varphi'(z_d - 0) = 4\pi Q \sigma.$$  

Here $\varphi$ is the potential, $\varphi' = \frac{\partial \varphi}{\partial z}$ and $\sigma$ is the surface density of the layer.

Several assumptions have been made throughout the calculations:

- The dust charge does not effect the equilibrium of the plasma electron and ion density;
- the absorption of ions by the dust layer is ignored;
- values of the surface density are sufficiently small;
- there is no tangential electric field (i.e. the shear stress is also 0);
- the electron pressure is neglected;
Sheath voids in a cloud of spherical dust particles

- the effect of the layer density on the sheath thickness is neglected.

The authors found that the negatively charged dust layer reduces the electric field between the dust layer and the electrode (i.e. in our case below the dust layer). The surface tension $s$ is defined as a tangential force (per unit length) acting between two parts of the plasma-electrode interface (i.e. the plasma sheath). The surface tension is calculated as a function of the surface dust density $\eta$. It is found that the surface tension $s(\eta)$ can decrease with increasing surface dust density. The horizontal force per unit length acting on the edge of a dust layer has been evaluated as:

$$F = s(\eta) - s(0).$$

In the case of decreasing surface tension with increasing surface density, i.e. negative force, the sheath expels the additional negative charge carried by the layer. The authors have evaluated also the force acting on the layer edge in absence of ions. The force is then positive. It is concluded that the negative force is a result of the self-consistent restructuring of the sheath under the influence of the charged layer. The appearance of a negative force may be interpreted as an attractive interaction between the dust grains.

In conclusion, the results of the above-presented model show that there are conditions, where the surface tension inside the void will be strong enough to prevent it from closing up.

4.5 Fluid model - W. Goedheer

The first numerical model, which was applied to our experimental conditions is a two-dimensional model, developed in the last 12 years under the supervision of W. Goedheer in the "FOM-instituut voor Plasmafysica Rijnhuizen", Nieuwegein, The Netherlands. It is a self-consistent model for a dust-containing RF discharge in argon. Here the basics of this model will be presented as well as the results for the specific conditions of our experiment: reactor geometry and plasma input parameters.

The modelling has been performed by W. Goedheer.

4.5.1 Plasma modelling

The plasma modelling is performed using a fluid model. It consists of:

- Particle balance equations for electrons, ions and meta-stables,
- Drift-diffusion approximation, which replaces the momentum balance,
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- Energy balance equation for electrons,
- Poisson equation for the electric potential.

In the plasma model, the density balance ($0^{th}$ moment of the Boltzmann equation) for a species $j$ (electron or ion) is given by:

$$\frac{\partial n_j}{\partial t} + \nabla \cdot \Gamma_j = S_j,$$

(4.4)

where $n_j$ is the $j$ species density, $\Gamma_j$ - the flux of the species $j$ and $S_j$ - their source. The particle flux $\Gamma_j = n_j \vec{u}$ is described using the so-called drift-diffusion approximation, in which the particle flux consist of one diffusive and one drift term:

$$\Gamma_j = \mu_j n_j \vec{E} - D_j \frac{\partial n_j}{\partial x},$$

(4.5)

where $\mu_j$ and $D_j$ are, respectively, the mobility and the diffusion coefficient of species $j$ and $\vec{E}$ is the electric field. At the applied RF frequency of 13.56 MHz, the ions do not follow the electric field. In order to account for this, in equation 4.5 the electric field is replaced by an effective electric field:

$$\vec{E} \to \vec{E}_{eff}.$$

The effective electric field is obtained by neglecting the diffusive term in equation 4.5 and substituting the expression for $\Gamma_i$ in a simplified [71] momentum balance:

$$\frac{\partial \Gamma_i}{\partial t} = \frac{e n_i}{m_i} \vec{E} - \nu_{m,i} \Gamma_i,$$

(4.6)

where $\nu_{m,i}$ is the momentum transfer frequency of the argon ions given by

$$\nu_{m,i} = \frac{e}{\mu_i m_i}.$$

(4.7)

Then the effective electric field is obtained by solving

$$\frac{\partial \vec{E}_{eff,i}}{\partial t} = \nu_{m,i} \left( \vec{E} - \vec{E}_{eff,i} \right).$$

(4.8)

The electric field $\vec{E}$ is determined using the Poisson equation for the electric potential $V$, taking into account the charge of the dust particles:

$$\nabla^2 V = -\frac{e}{\varepsilon_0} \left( n_i - n_e - Q_{dust} n_{dust} \right),$$

(4.9)
Sheath voids in a cloud of spherical dust particles

\[ E = -\nabla V. \]  \hspace{1cm} (4.10)

Here \( Q_{\text{dust}} \) is the charge of the dust particle and \( n_{\text{dust}} \) is the dust particle density.

Only the electron energy balance is taken into account. The electron energy is determined via the second moment of the Boltzmann equation:

\[ \frac{\partial n_e \varepsilon_e}{\partial t} + \nabla \cdot \Gamma_{e} = -e \Gamma_{e} \cdot E + S_w, \]  \hspace{1cm} (4.11)

where

\[ \Gamma_{e} = \frac{5}{3} \mu_e n_e \varepsilon_e E - \frac{5}{3} D_e \nabla (n_e \varepsilon_e). \]  \hspace{1cm} (4.12)

More information can be found in the thesis of Passchier [71].

4.5.2 Dust transport modelling

The dust transport modelling is also based on the fluid model. Here we will give briefly some important aspects of the model.

4.5.2.1 Dust particle charging

An important aspect of the dust implementation in the model is the dust charging. In the model the Orbital Motion Theory is used. The charge of the dust particle is calculated from the equilibrium of the ion (eq. 2.22) and electron current (eq. 2.24) to the particle. In order to account for the directed motion of the ions in the sheath in front of the electrode the thermal energy \( kT_i \) is replaced by the mean energy \( E_i \):

\[ kT_i \rightarrow E_i = \frac{4kT_{\text{gas}}}{\pi} + \frac{1}{2} m_i v_i^2. \]

The dust charge is considered constant during the RF cycle. The heating of the dust particle due to the recombination of electrons and ions on its surface is also taken into account.

4.5.2.2 Forces acting on the dust particle

The forces, acting on the dust, which are taken into account are:

- gravity - equation 2.35;
- electrostatic - equation 2.36;
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- neutral drag - equation 2.39;
- ion drag - equations 2.43 and 2.46;
- thermophoretic - equation 2.49.

Previous calculations have shown that the ion drag force has to be enhanced by a factor of 5 (or the linearized Debye length, participating in the expression of the orbit ion drag force to be replaced by the electron Debye length) in order to achieve a void in the bulk dusty plasma [72]. This factor has been used in the modelling of our setup.

The dust particles are modelled also as a fluid. For this purpose, a "drift-diffusion" expression for the dust particle flux is defined as:

$$
\overrightarrow{\Gamma}_d = -\mu_d n_d \overrightarrow{E}_{eff} - D_d \nabla n_d - \frac{n_d}{\nu_{md}} \overrightarrow{g} + \frac{n_d m_i v_s}{m_d \nu_{md}} \left(4\pi b_1^2/2\Gamma + \pi b_c^2\right) \overrightarrow{\Gamma} + \frac{32}{15} \frac{n_d v_d^2}{m_d \nu_{md} \nu_{th}} k_f \nabla T_{gas},
$$

(4.13)

where momentum loss frequency $\nu_{md}$, mobility $\mu_d$ and diffusion coefficient $D_d$ are introduced as follows:

$$
\nu_{md} = \sqrt{\frac{2}{k_B T_{gas}}} \frac{p_{tot}}{\pi r_d^2} \sqrt{\frac{8k_B T_{gas}}{\pi m_d}},
$$

(4.14)

$$
\mu_d = \frac{Q_d}{m_d \nu_{md}},
$$

(4.15)

$$
D_d = \mu_d \frac{k_B T_{gas}}{Q_d}.
$$

(4.16)

4.5.3 Results of the modelling

The results of the model did not agree with the experimental observations. No void formation has been observed in the numerical simulation. Even the increase of the ion drag force by 5 times, which has been enough to simulate the void creation in the bulk plasma, observed in micro-gravity conditions, did not result in a void in the sheath. The simulations did not result in horizontal force acting on the particles radially outwards.

In figure 4.12 a map of the plasma potential calculated via the above-presented model is given. This graph does not show structuring of the electrical features in the sheath as observed via the Langmuir probe measurements of the floating potential (see figure 4.9).
Sheath voids in a cloud of spherical dust particles

Figure 4.12: Plasma potential according to the fluid model. The plasma parameters for this simulation are: pressure of 40 Pa, gas temperature of 273 K and RF voltage of 300 V. Courtesy W. Goedheer.

Even though the results of this model did not agree with the experiment, it appeared to be very useful in the analysis of the void phenomenon, as will be shown in section 4.7.

4.6 Hybrid model - M. Kushner, V. Vyas

The second numerical model, which was applied to our experimental conditions, has been developed in the last 10 years under the supervision of M. Kushner in the group "Computational, optical and discharge physics", University of Illinois. This is a self-consistent 2-D model. It is a hybrid model, i.e. it contains both fluid and kinetic simulations. The dust particle transport model is integrated in a plasma equipment model.

The modelling has been performed by V. Vyas.

4.6.1 Plasma modelling

The modelling of the plasma is based on the Hybrid Plasma Equipment Model (HPEM) [73, 74]. This model consists of several modules, of which
two are used:

- electron energy transport module (EETM): calculates electron temperature, impact sources and transport coefficients;
- fluid kinetic module (FKM): calculates densities, momenta and temperatures of charged and neutral plasma species and electrostatic potentials.

In the EETM module the electron transport coefficients (mobility, diffusion coefficient, thermal conductivity) and the sources for their impact processes are generated. This is achieved by resolving the electron energy transport by solving the electron energy conservation equation. Finally the FKM module solves:

- continuity equations for ions and neutrals,
- momentum equation for ions and neutrals,
- energy equation for ions and neutrals,
- drift-diffusion continuity equation for electrons,
- Poisson equation for the electrostatic potential.

4.6.2 Dust transport modelling

The dust transport modelling is performed using the Dust Transport Simulation (DTS) module [75]. It is a three-dimensional model.

4.6.2.1 Dust particle charging

In this model, the dust charge is determined in a similar way as in the model of W. Goedheer. The floating potential of the particle is determined by the equality of the ion (eq. 2.22) and electron current (eq. 2.24) to the dust particle. The charge on the particles is determined by the capacitance model.

4.6.2.2 Forces acting on the dust particle

The forces taken into account in this model are:

- gravity - equation 2.35;
- electrostatic - equation 2.36;
Sheath voids in a cloud of spherical dust particles

- ion drag;
- neutral (or fluid) drag;
- thermophoretic;
- Coulomb;
- self-diffusion;
- Brownian.

The orbital cross section $\sigma$ in the ion drag force is calculated according to the semi-analytic formula of Kilgore [47]:

$$
\sigma_{\text{orb}} = c_1 b^2 \ln \left( 1 + \frac{c_2}{\beta^2} \right),
$$

(4.17)

where $c_1 = 0.9369$, $c_2 = 61.32$, $b = \frac{Z\mu e^2}{4\pi\epsilon_0 \frac{4}{3} \pi a^3}$ and $\beta = \frac{b}{x_D}$.

The neutral drag force is calculated using the following formula:

$$
F_{\text{ND}} = -6\pi \mu r_d \left( \bar{v} \cdot - \bar{u} \right) C_D(Re) \frac{Re}{24},
$$

(4.18)

where $\mu$ is the gas viscosity, $C_D(Re) \frac{Re}{24}$ is the correction due to inertial effects and $C(Kn)$ - the slip correction factor:

$$
C_D(Re) \frac{Re}{24} = 1 + 0.173 Re^{0.657} + \frac{0.01721 Re}{1 + 16300 Re^{-1.09}},
$$

(4.19)

$$
C(Kn) = 1 + Kn \left( \alpha + \beta \exp\left( -\frac{\gamma}{Kn} \right) \right).
$$

(4.20)

Here the Reynolds number for particles $Re$ is defined by $Re = \rho |\bar{v} - \bar{u}| / \mu$, $Kn$ is the Knudsen number. Usually the inertial correction factor is nearly equal to unity.

The thermophoretic force used in the DTS module is calculated by the following formula:

$$
F_{\text{th}} = -6\pi \mu r_d \nu K_T \frac{\nabla T}{T}.
$$

(4.21)

Here the slip correction factor $K_T$ is as developed by Talbot et al. [51].

$$
K_T = \frac{2C_s \left( k_s \nu + C_l Kn \right)}{(1 + 3C_m Kn) \left( 1 + 2k_s \nu + 2C_l Kn \right)},
$$

(4.22)
where \( k_g \) and \( k_p \) are the gas and particle thermal conductivities; \( C_t, C_s \) and \( C_m \) are the thermal creep coefficient, temperature jump coefficient and velocity jump coefficient, respectively.

The Coulomb repulsive force between the particles is based on the particle’s shielded potential in the Debye-Huckel form [76]:

\[
V(r) = V_0 \frac{r_d}{r} \exp\left(\frac{r - r_d}{\lambda_D}\right).
\]

Then the inter-particle Coulomb force between 2 particles positioned at \( \mathbf{r}_1 \) and \( \mathbf{r}_2 \), i.e. at distance \( R = |\mathbf{r}_1 - \mathbf{r}_2| \) is

\[
\mathbf{F}(\mathbf{r}_1, \mathbf{r}_2) = \frac{Q_1 Q_2}{4 \pi \varepsilon_0} \frac{1}{R} \left(1 + \frac{1}{\lambda_D}\right) \exp\left(-\frac{R - \frac{(r_{d1} + r_{d2})}{2}}{\lambda_D}\right) \frac{\mathbf{r}_1 - \mathbf{r}_2}{R}.
\]

Calculating the force for certain particle \( i \) with radius \( r_d \) we have to take into account the interaction with all the particles:

\[
\mathbf{F}_{\text{Coulomb}} = \frac{Q_i}{4 \pi \varepsilon_0} \sum_j \frac{Q_j}{R_{ij}} \left(\frac{1}{R_{ij}} + \frac{1}{\lambda_D}\right) \exp\left(-\frac{R_{ij} - r_d}{\lambda_D}\right) \mathbf{r}.
\]

In the model the maximum interaction distance is set to \( 5 \lambda_D \) in order to reduce the calculation time.

The force, which is associated with the Brownian motion, is also included in the model but it is negligible for all cases of interest here, due to the large particle size.

The last force included in this model is the self-diffusion force:

\[
\mathbf{F}_{\text{self-diffusion}} = -kT_d \nabla N_d,
\]

where \( N_d \) is the dust particle concentration and \( T_d \) - their temperature, determined by their thermal energy (eq. 2.51).

### 4.6.3 Results of the modelling

The simulations performed with the hybrid model described in this section do show void existence at certain plasma conditions. The experimentally observed trends in the dependence of the void on these parameters is also present: the void appears and grows with increasing power and pressure.

In figure 4.13 the particle position in the horizontal plane is depicted at four different power values. The simulation is performed for 25 particles.
It is seen that at low power range the cloud appears compact and its size grows with the power. The simulation shows that the threshold power, at which the void appears, is between $15W$ and $20W$. If we compare this to the experimental data represented in figure 4.2, we see that this threshold power is about $10W$ below the experimental threshold power, which appears between $25W$ and $30W$. However, as it has been discussed in Chapter 3, the power measured by the Bird power-meter is systematically larger than the power supplied to the plasma. Thus the discrepancy between the experimental and simulated threshold is most probably due to the systematic error in the measured power in the experiment.

In figure 4.14, analogically, the particle positions as function of pressure are presented for 25 particles levitating in the sheath of a $10W$, $10sccm$ plasma. The simulations predict void appearance somewhere in the range between $19Pa$ and $27Pa$. The threshold pressure in the experiment per-
formed at the same power of 10W appears between 17.5Pa and 19.5Pa.

\[
\begin{array}{cc}
(a) & 11 \text{ Pa} \\
(b) & 19 \text{ Pa} \\
(c) & 27 \text{ Pa} \\
(d) & 32 \text{ Pa}
\end{array}
\]

Figure 4.14: Top view of the particle positions above the 3cm circular depression in the powered electrode as a function of pressure. The simulation has been performed for 25 10\(\mu m\)-diameter particles in an argon plasma at a power of 10W, and a gas flow of 10sccm. Courtesy of V. Vyas

In table 4.1 the results on the void formation threshold from the experiment and the model are summarized.

<table>
<thead>
<tr>
<th></th>
<th>power dep. (at 19 Pa)</th>
<th>pressure dep.(at 10W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>exp.</td>
<td>25 – 30W</td>
<td>17.5 – 19.5Pa</td>
</tr>
<tr>
<td>model</td>
<td>15 – 20W</td>
<td>19 – 27Pa</td>
</tr>
</tbody>
</table>

Table 4.1: Comparison of experimental and theoretical values for the threshold for void formation
4.7 Comparison of the two models

The results of the two models described in the previous sections 4.5 and 4.6 differ from each other. The results of the hybrid model in section 4.6 show the experimentally observed phenomenon of void formation in the cloud. The model from section 4.5 does not reach void-like structuring of the dust cloud in the working range of pressure and power. The goal of this section is to systematically compare the two models described in sections 4.5 and 4.6. This comparison can give us a clue for the possible reason for void formation.

In order to make a proper comparison of two models, a full comparison should be made based on all the main components of the models:

- equations;
- coefficients: cross sections (and from there reaction rate coefficients), transition probabilities (radiation), surface coefficients (secondary emission coefficients, photo-induced emission coefficient);
- boundary conditions;
- initial conditions;
- geometry;
- discretization scheme.

Both simulations have been ran for our particular set-up configuration, i.e. the geometry is the same. We are looking for a steady-state solution. Both models reach convergence of the solution. Thus, we can assume that the initial conditions are not of importance for the comparison of the models. We assume also that in both cases the discretization is fine enough in order not to have effect on the results. The model of W. Goedheer assumes the following boundary conditions:

- all surfaces except the bottom electrode are grounded ($V = 0$) and the lower electrode is powered and its voltage is dynamically adjusted to get the desired power deposition;
- the electron density at the walls is $n_e(\vec{r}, t) = 0$;
- the positive ion flux in the direction perpendicular to the electrodes is fully a drift flux, i.e. the gradient in the ion density in that direction is zero $\vec{n} \cdot \text{grad} n_i = 0$. 

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Chapter 4

In the second model only the boundary condition for the ions differs - it is assumed that the ion density at the wall is zero \( n_i = 0 \). It is assumed that this affects only a narrow region near the surface and does not influence the dust particle position.

Therefore we will concentrate further on the comparison of the physics implemented in the two models (equations and assumptions included in these equations). This comparison is presented in table 4.7.

<table>
<thead>
<tr>
<th>Features</th>
<th>Goedheer</th>
<th>Kushner</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Plasma</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Density balance</td>
<td>for e, ions and neutrals</td>
<td>for e, ions and neutrals</td>
</tr>
<tr>
<td>momentum balance</td>
<td>drift-diffusion approximation</td>
<td>drift-diffusion approximation</td>
</tr>
<tr>
<td>- electrons</td>
<td></td>
<td></td>
</tr>
<tr>
<td>momentum balance</td>
<td>drift-diffusion approximation</td>
<td>momentum equation</td>
</tr>
<tr>
<td>- ions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>energy balance</td>
<td>for electrons</td>
<td>electrons (in EETM)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ions, neutrals (in FKM)</td>
</tr>
<tr>
<td>electric field</td>
<td>Poisson</td>
<td>Poisson</td>
</tr>
<tr>
<td></td>
<td>(incl. dust particles)</td>
<td></td>
</tr>
<tr>
<td><strong>Dust</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Charge</td>
<td>OML</td>
<td>OML</td>
</tr>
<tr>
<td>Forces:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>gravitational</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>electrostatic</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>ion drag</td>
<td>eq. 2.46; ((5))</td>
<td>eq. 4.17</td>
</tr>
<tr>
<td>neutral drag</td>
<td>eq. 2.39</td>
<td>eq. 4.18</td>
</tr>
<tr>
<td>thermophoretic</td>
<td>eq. 2.49</td>
<td>eq. 4.21</td>
</tr>
<tr>
<td>self-diffusion</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td></td>
<td>(second term in eq. 4.13)</td>
<td>(eq. 4.26)</td>
</tr>
<tr>
<td>Brownian</td>
<td>no</td>
<td>yes, but negligible</td>
</tr>
<tr>
<td>Coulomb</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td></td>
<td>via Poisson equation 4.9</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.2: Comparison of the equations and assumptions in the models “Goedheer” and “Kushner”

The density and momentum balances in both models have been solved for all the plasma components (electrons, ions and neutrals). For electrons, both models use the drift-diffusion approximation for the momentum balance for electrons. For ions, in the fluid model of W. Goedheer the drift-diffusion approximation is used as well, while in the hybrid model of M. Kushner the
full momentum balance has been solved. The energy balance in the fluid model is not solved because the ion temperature does not differ a lot from the neutral temperature. By assuming drift-diffusion approximation for the ions in the fluid model, the convective derivative and the term accounting for the inelastic collisions are neglected. Analysis of these terms is performed in the thesis of D. Passchier [71]. Neglecting inelastic collisions is justified as the ionization rate of a plasma at our conditions is not high. In the thesis of D. Passchier, it has been acknowledged that the convective derivative is not necessary small in the sheath. As the phenomenon discussed in this chapter appears in the plasma sheath and the fluid model does not manage to simulate the effect, we consider that this assumption is essential for the differences between the two models.

The dust charging has been calculated in both models using the OML theory. There are certain differences in the force balance on the particles. In the hybrid model Brownian force has been included. For large particles as it is the case in our experiments, this force is however negligible. Some of the forces have been used at different stages of the calculations, i.e. the self-diffusion and the Coulomb interaction force (see table 4.7). For other forces different expressions have been used, i.e. for the ion drag, neutral drag and thermophoretic force. The neutral drag force in the case of a static cloud and at a position in the experimental set-up where the gas flow is negligible would not attribute to the explanation of the appearance of a void in the dust cloud. Therefore, we will not discuss the differences in these expressions.

The thermophoretic force in the fluid model has been included in the form for the collisionless limit \((\text{Kn} \to \infty)\) derived by Talbot [51] - eq. 2.49. In the hybrid model, the fitting formula proposed by Talbot [51], which agrees very well in the collisionless limit with equation 2.49, is used. In our case, the maximum mean free path (at the lowest pressure of 4 Pa) has been estimated \(l_{mfp} = 1.3 \text{ mm}\) (see section 2.2.1.3) and the radius of the dust particles is \(r_d = 4.9 \mu\text{m}\). The Knudsen number in this case is \(\text{Kn} = 130\). In this case, we assume that the difference between equations 2.49 and 4.21 is negligible. At higher pressures 40 Pa, the mean free path is \(l_{mfp} = 0.13 \text{ mm}\), which results in \(\text{Kn} = 13\). In this case, the formula used in the hybrid model would give a more precise value for the thermophoretic force. The formula used in the fluid model is giving higher estimate of this force. Based on this analysis, we can conclude that the thermophoretic force is not the cause of the void formation, discussed in this chapter, as the model, which does not simulate the void, is using larger value for the thermophoretic force.

For the calculation of the ion drag force, in the fluid model of W. Goedheer the formula of Barnes eq. 2.46, which assumes cut-off Coulomb potential, has been used. It is well known that this formula underestimates the ion drag
force. Therefore the multiplying of this force by factor of 5, as done in
the model, is justified. Most of all, this factor has been chosen in previous
work [72] in order to explain void formation in the bulk plasma in the PKE
chamber [25]. In the hybrid model of M. Kushner, the semi-analytical formula
of Kilgore, has been used. Kilgore has shown that this formula is fitting
very well the numerical calculations of cross section for the Poisson-Vlasov
potential. We assume the factor 5 introduced in the fluid model accounts for
the difference in the ion drag force, calculated via equations 2.46 and 4.17.

Based on the comparison of the two models, we can conclude that the
difference in their results is most probably due to the different ion momentum
balance. Therefore, the most probable reason for void formation is the ion
flow in the plasma sheath.

4.8 Conclusion

We have observed voids in dust clouds levitated in the plasma sheath. In-
vestigation of the void dependence on the plasma parameters (pressure and
RF power) is carried out. In order to characterize the electric potential pro-
file above the electrode depression Langmuir probe measurements have been
performed. At higher pressures the profile of the floating potential (measured
with respect to ground) shows transition from a structure with a maximum
at the axis to a structure with two maxima off axis. As a first step in the
model-based analysis of the void phenomenon, a phenomenological model has
been presented. The model prediction of the void diameter trend with power
and pressure matches very well the observed curves, after being calibrated
on one data point. Secondly, the surface tension theory developed by Ignat-
tov et al. [69] triggered by our experimental observations is briefly explained.
Both models concern the cloud size development but do not propose a driving
force for the initial void formation.

Finally, two plasma-dust simulations have been run for the particular
conditions of our set-up. Their results differ substantially. The hybrid model
is the only one obtaining void formation in our working range of parameters.
Analysis of the differences in the two models has been performed in order to
determine which are the important plasma features causing the phenomenon.
The conclusion of this comparison is that the radial component of the ion
flow is the major cause of void formation.
Chapter 5

Orbiting of dust particles in the potential trap of a non-magnetized plasma


5.1 Introduction

In this chapter we treat orbiting of dust particles in the circular potential trap above the depression in the lower powered electrode. "Orbiting" is a term used for particle rotation with constant angular velocity around the axis of the trapping depression.

There have been many articles reporting orbiting of dust particles observed in magnetized plasmas [77–81]. The orbiting of the particles in those experiments is considered due to the azimuthal drift of the ions in crossed radial electric and vertical magnetic field. In our experiment, we do not apply an external magnetic field.

In the experiments discussed here we have injected spherical particles with diameter \( d = 9.8 \mu m \). Some of the injected particles orbit, while most of them form a cloud, which can be in gaseous (randomly moving), liquid (locally moving) or Coulomb crystal state (the particles have stable position and form a crystal-like pattern). In all observations, the orbiting particles, are positioned lower than the main cloud. This implies that these particles
are heavier. A logical suggestion is that the particles are agglomerates of the originally injected melamine formaldehyde spherical particles or pollutants. Thus, they are most likely non-spherical.

Most of the experimental research on micrometer-sized particles in laboratory plasmas has been performed using spherical particles. This simplifies the problem and often allows to consider the dust particles as point-like objects. Nowadays, there is detailed information on dusty plasmas containing spherical particles [5].

In an astrophysical environment, coagulation is an important dust growth process [82]. As a result, cosmic dust is often of irregular form. Thus, the behavior of non-spherical particles is of great interest for astrophysics. The knowledge from laboratory dusty plasma experiments, based only on spherical grains, is not sufficient for a comparison with space dusty plasmas. Formation of irregularly shaped structures, in particular strings and V-shaped particles, happens also in laboratory methane plasmas [83]. Recently, there has been increasing interest in investigation of dusty plasmas, containing non-spherical particles, in particular rod-like ones [84, 85].

The laboratory experiments reported here deal with the behavior of dust particles, which are considered non-spherical. The results give additional insight in the complexity of this type of dusty plasma.

In section 5.2, the experimental observations on orbiting of particles trapped in the sheath of a radio-frequency capacitively-coupled RF plasma are presented. The observed pressure and power dependence of the movement as well as transition between different orbits are discussed.

The order of magnitude of the driving force is estimated in section 5.3. The features of the rotation and the properties of the driving force are also discussed. Based on these properties, we propose the orbiting of non-spherical particles to be related to the ion drag force.

In section 5.4, we offer a comparison of our experimental work with some previous experiments, in which a circular motion of dust particles has been observed. Here we point out the differences and verify the novelty of the work presented in this chapter.

In section 5.5, we discuss the forces acting on particles with different forms. It is concluded that for particles with spherical, cylindrical (rod-like particles) or axial symmetry orbiting in the potential trap is not likely.

In section 5.6, two possible mechanisms based on the ion flow are proposed. The first one is a sailing-like effect. Assuming that a rod-like particle can be in a steady position tilted with respect to the electric field, we estimate the order of magnitude of the ion sailing force. This case is used as first approximation to the more complicated case of irregular shaped particle. The second mechanism considers spinning particles. We show that for labo-
ratory plasma the effect of this mechanism is negligible, but it can become considerable in the conditions of stellar wind plasmas.

5.2 Experimental observations

In this section, experimental observations on the orbiting of isolated particles below the main dust cloud of 9.78\(\mu\)m melamine-formaldehyde dust particles will be addressed.

5.2.1 Position of the orbiting particles with respect to the dust cloud

5.2.1.1 Vertical position

In the experiments discussed here, we inject in the plasma melamine formaldehyde spherical particles with diameter \(d = 9.78\mu m\). Nevertheless, the side view images (see figure 5.1) show that there are often some particles levitated below the main cloud. In first approximation, the vertical position of the particles in the plasma is determined by the equilibrium of the electric force \(\vec{F}_E = Q_D \vec{E}\) and the gravitational force \(\vec{F}_g = m_D \vec{g}\). Assuming that the density of the particles is the same and that the ion and electron density and temperature are constant in the sheath, we can conclude that the particles levitating lower in the plasma sheath have a larger radius and therefore, a larger mass.

As we inject mono-disperse particles in the plasma, a question about the source of larger particles arises. A reasonable explanation is that due to ageing some of the particles have coagulated. Microscope pictures of the melamine-formaldehyde particles we use (see figure 3.5 in Chapter 3) support this explanation. We can see that the particles tend to stick together. If we assume that this is the reason for the presence of heavier particles in the plasma, we can conclude that these particles are not spherical.

Often these heavier particles orbit frictionless. Here we will focus on their behavior.

We have never observed particles rotating in the layer of the main cloud. This is in agreement with our assumption that only the non-spherical agglomerated particles can orbit. They are heavier than the spherical particles in the main cloud and therefore not at the same height. Only particles lying below the main dust cloud perform orbiting. The vertical position of the particles is a necessary but not sufficient condition for orbiting.
5.2.1.2 Horizontal position of the orbit regarding the dust cloud

In all the experiments, discussed in this chapter, the dust cloud is trapped above the center of the depression in the electrode. The cloud is usually in a gaseous form. Dependent on the plasma conditions, this cloud can have different shapes. It can be compact or it can have an annular form, i.e. with a void in the middle (see figure 4.1 in Chapter 4).

The orbits of the particles are restricted by the edge of the trapping depression of the electrode, which gives an inwards electrostatic force on the particles. The position of the orbits relative to the main cloud depends on the shape of the cloud. If the cloud is compact and small (cloud diameter is about $3\text{mm}$), the orbiting particles are positioned outside at a relatively large distance (about $2\text{mm}$) from the edge of the cloud. In the case of a bigger cloud, the orbiting is usually in the periphery of the cloud. And if we have a cloud with a void developed in the middle, the particles can orbit outside the cloud, under it or inside the void. The absolute orbiting radius will be analyzed as function of power and pressure in sections 5.2.3 and 5.2.4.

5.2.2 Direction of orbiting

We have observed that two different particles can simultaneously rotate in opposite directions (clockwise and anti-clockwise). The radii and angular
velocities in most of these cases are comparable, though not identical. Figure 5.2 visualizes the orbiting of 4 particles around the main cloud. The orbiting particles are presented by an arrow in the direction of motion. Three of the particles rotate anti-clockwise and one - clockwise. The length of the arrows is proportional to their velocity. There is no dependence of the orbiting direction on the distance to the center.

The presence of two different orbit directions shows that the orbiting is not due to directional drag from the ion flow, e.g. due to magnetic field, as it is considered in the cases of orbiting particles in magnetized plasmas [77–79]. When two particles moving in opposite directions approach each other, they deviate from their orbits due to the repulsive electrostatic forces.

![Figure 5.2: Top-view picture of particles, some of which orbit. The orbiting particles are represented by arrows in the direction of movement. The length of the arrows is proportional to the speed of the particles. The main cloud is visible in the center.](image)

We have observed a case of particle changing orbit direction while we change power. This means that there is no essential difference between the particles orbiting in different directions, i.e. the different direction is not due to a permanent feature of the particles. Most probably, a different orientation of the particles in the electric field of the sheath causes the different orbit directions.
5.2.3 Pressure dependence

There is a clear dependence of the rotation of the orbiting particle on the plasma parameters. Both rotation frequency and orbit radius are influenced by changes in the plasma parameters.

Figure 5.3: Pressure dependence of the frequency (a) and orbit radius (b) of a rotating particle levitating below a dust cloud of mono-disperse melamine formaldehyde particles in an argon plasma at 30W. The particles are trapped above an electrode depression with a diameter of 30mm. The bold black line shows the linear fit on the pressure dependence of the orbit radius.
Figure 5.4: The corresponding linear speed as function of the gas pressure. The curve has a maximum at $33\text{Pa}$, which implies that above this pressure the driving force increases more slowly than the neutral drag frictional force.

In figures 5.3 and 5.4, we present data from the analysis of the orbiting motion of a large particle in the presence of a mono-disperse particle cloud. The experiment is performed in argon at constant radio-frequency power of $30W$.

In figure 5.3, the pressure dependence of the orbit frequency $\nu_{\text{orb}}$ and radius $r_{\text{orb}}$ is presented. The error in measurement of the orbit radius is $\Delta r_{\text{orb}} = 0.5mm$ introduced by the increase of the visible particle size due to its spinning. Within this error, the orbit radius is increasing linearly with the pressure through the whole range of pressure. As can be seen from the graph, at low pressures the rotational frequency decreases with the pressure. Above $26\text{Pa}$, it starts increasing with the pressure. At $33\text{Pa}$, the rotational frequency reaches a maximum followed by a decrease.

It is surprising that both frequency and radius increase with pressure as it seems that in spite of increased friction the particle moves faster. This is even more obvious from figure 5.4, where the linear speed is plotted against pressure. The only possible explanation of this feature of the orbiting is that the driving force increases faster with pressure than the frictional force.
5.2.4 Power dependence

The dependence of the orbit parameters on the power shows similar behavior as the one on the pressure. Note that the particle, for which the orbiting will be discussed here, is not the same particle as in the previous section.

![Graph of frequency of rotation vs. power](a)

![Graph of orbit radius vs. power](b)

Figure 5.5: Dependence of the frequency of rotation (a) and the orbit radius (b) of a big non-spherical particle on the applied power.

The experiment is performed in argon at constant pressure $p = 18.5\text{Pa}$. Through the experiment, the main dust cloud has the form of a ring with a
void in the middle. In figures 5.5 and 5.6, we give data on the rotation of a heavier non-spherical particle in the presence of this cloud.

In figure 5.5, a graph of the rotational frequency of the particle and its orbit radius as function of the applied power is presented. The circles represent the experimental data on rotational frequency and the diamonds - on orbit radius. At low powers (in the range 4 to 20W), the particle under consideration is not orbiting. The data on orbit radius in this range should be treated as distance of the particle from the center of the trap. At 4W, the particle is in a stable position at a distance of 5.7mm from the center. After we increase the power to 10W, the particle starts to spin (rotate around its own axis). At these conditions, the particle still does not orbit in the trap. At the same time there is another particle, which is orbiting. The latter appears smaller and we cannot recognize if it is spinning or not. Above 20W, the spinning particle starts orbiting under the cloud and the frequency increases with the power. At 60W, the frequency reaches a maximum. The orbit radius has a different behavior. At low powers, it decreases and, after a minimum at 34W, it starts increasing again.

Figure 5.6: Dependence of the linear speed (corresponding to the frequency and radius from figure 5.5) of the particle on the power.

In figure 5.6, the power dependence of the linear speed of the orbiting particle is given. Even though the distance of the particle from the center is decreasing at low powers, this does not have effect on the linear speed curve, as at these low powers, there is no orbiting of the particle.
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5.2.5 Spinning

As we have mentioned already, in many cases the orbiting particles were performing also spinning motion. At low power (below 10W) no spinning has been observed. The spinning threshold is not the same for all the particles. In the case of particles performing both spinning and orbiting, with increasing power, they initially start spinning and only further increase of the power results in orbiting motion. A priori, it is not clear if there is a direct connection between the spinning and the orbiting motion. Both motions appear with increasing power, i.e. with increasing the energy in the system, suggesting they are not independent from each other. In section 5.6 we will propose a mechanism based on the spinning of the particle and we will estimate the connection with orbiting.

There are several theoretical models for the spinning motion of spherical particles. Ishihara [86] assumes that a particle would be dragged by the rotating ion flow around the particle, while Tsytovich [87] considers spinning of particles due to asymmetry in the charging process. It is likely that the non-spherical form of the charged particle would give an additional contribution to the spinning motion.

5.2.6 Transition between orbit around the cloud and orbit in the void

By further increasing the power to 68W in the experiment, described in section 5.2.4 and figures 5.5 and 5.6, a novel phenomenon was observed. The orbiting and spinning particle started to oscillate in the radial direction as well. The resultant trajectory is sketched in figure 5.7. The movement of the particle is a superposition of rotation and oscillation in radial direction. This makes the length of its trajectory during a period longer. Although the period for a full turn is longer, the linear speed of the particle still reaches higher values, indicating a continuous increase of the driving force with power. The change in the orbit form is likely due to a more flat potential well.

After several minutes, the particle made a spontaneous transition from this trajectory to a circular one in the void. During the orbiting in the void, the damping force appeared to be larger than the driving force and the velocity of the particle slowly decreased. Two minutes later the particle stopped in the middle of the void.
5.3 Analysis of the driving force

In all our observations, the orbiting particles have been positioned at a lower level than the main dust cloud, consisting of spherical particles. Thus, we suggest that only the heavier non-spherical particles can orbit in our plasma configuration in the absence of magnetic field. In experiments with rod-like particles at the same plasma conditions we do not observe the particles orbiting. Molotkov et al. [84] and Annaratone et al. [85], who have performed experiments with rod-like particles too, do not report either on orbital motion of the rod-like particles. Thus we can put a further constraint on our assumption, namely that only particles with irregular form can orbit in the trap.

There is a previous observation of a cloud with configuration similar to ours - mono-layer cloud in the sheath and single particle under it [88, 89]. In this experiment, a single particle beneath the lattice plane is moving faster than the lattice sound speed and creates mach cones. Recently, an explanation of the mechanism for acceleration of this particle has been proposed [90], based on the asymmetric inter-particle interaction between particles in the upper and lower layer, due to the ion wake-field, induced under a particle in the sheath by the flowing ions.

As we have observed orbiting of the particles not only in the presence
of a cloud, but also in cases of single particle in the plasma, we can deduce that the orbiting in our experiments is not a collective effect. Thus, the mechanism proposed in [90] cannot explain our observations.

5.3.1 Trajectory

As already mentioned, the equilibrium of the forces acting on a particle (see figure 5.8) in the plasma determines its position. In the vertical direction, the particle is trapped at the position where the vertical part of the electric force is equal to the gravitational force. In our case, the particles are trapped in the sheath. The depression in the lower electrode creates a curved electric sheath, which in terms of forces means that we have an additional radial component of the electric force and also of the ion drag force, as the ions are accelerated in the electric field. Thus the equation of motion of an orbiting particle in the horizontal sheet will involve the neutral drag, electric and ion drag forces (see figure 5.9).

The radial electric force decreased by the radial ion drag force plays the role of the centripetal force. This limits the horizontal movement of the dust particles. Therefore, their trajectories are confined within the area of the trap.

As the neutral drag force is damping the motion, a driving force is necessary for the particle to keep moving on the same orbit.
Orbiting of dust particles ...

Figure 5.9: Forces acting on a spherical particle in the sheath above the trap. $F_{\text{driving}}$ is the unknown driving force; the neutral drag force $F_{\text{ND}}$ is acting opposite to the movement; the role of centripetal force is played by the radial component of the electric force $F_{E, \text{radial}}$, which is decreased by the radial component of the ion drag force $F_{i, \text{radial}}$.

5.3.2 Order of magnitude

The orbiting of the particle below the cloud appears undamped. Thus, we can estimate the driving force by estimating the neutral drag damping force. To keep the particle moving with constant velocity the driving force should be equal to the neutral drag force. Let us make a rough estimate of the neutral drag force, assuming a dust particle radius five times larger than the one of the originally injected particles. Even at the maximum measured particle speed (16 mm/s), we are still far below the high-relative-speed condition (see Chapter 2) and thus we can use the Epstein formula for the neutral drag force. The neutral drag force is estimated for a pressure of 18.5 Pa, which is the pressure for the experiment reported in section 5.2.4, a gas temperature of 300 K and for the maximum measured particle speed. Using these values in equation 2.39, we find $F_{ND} = 2 \times 10^{-13} N$. Thus, this is also the expected value for the still unknown driving force.
5.3.3 Features of the driving force

In the experiment dealing with the pressure dependence of the orbiting, we have measured that below \(33 \text{ Pa}\) the linear speed of the particle is increasing with the pressure. The damping neutral drag force is proportional to the pressure. From this fact, we can draw the conclusion that in this range of pressures \(p < 33 \text{ Pa}\) the driving force increases faster than linearly with the pressure. For higher pressures the force seems to saturate.

In the working range of pressures, in argon there is linear dependence of the electron and ion density on the pressure \([67]\). Above \(40 \text{ Pa}\) Bisschops \([67]\) has observed saturation in the electron density increase. As the neutral drag force increases linearly with pressure, while the ion drag force saturates, we can expect a maximum in the linear speed of the orbiting particle at about \(40 \text{ Pa}\), which is in good agreement with our experiments.

The power dependence of the orbiting speed of the particle shows that the driving force also increases with power. By increasing the RF power of the plasma, the kinetic energy of the rotating particle also increases. There is a linear relation between applied RF power and electron and ion density in an argon plasma in the range up to \(40 \text{ W}\) \([67]\). As the ion flow is proportional to the ion density, we can conclude that the increase of the speed of the orbiting particles is connected to the ion flow.

The dependence of the particle velocity on power and pressure has a similar behavior as the dependence of the ion flow on power and pressure. Thus, the particle orbiting can be attributed to the ion drag.

5.4 Comparison with previous experiments

Here we will make a review on the previous experiments, in which movement of dust particles has been observed, in order to demonstrate the originality of our experiments and results.

5.4.1 Experiments with external magnetic field

There have been several experiments, in which rotation of particles has been observed while applying magnetic field \([77–81]\). The orbiting of the particles in most of these experiments \([77–80]\) is attributed to the azimuthal drift of the ions in a crossed radial electric and vertical magnetic field. Kaw et al. \([91]\) have published a letter with possible interpretation of the results from the article of Sato \([78]\), based on fluid equations. In the newest article, dedicated to experiments in dusty plasma in the presence of magnetic field, Amatucci et al. \([81]\) report direct observations of dust cyclotron motion of
alumina particles with a diameter of $1.2\mu m$ in magnetic field with strength $B = 2500G$. They estimate the dust particle gyrofrequency:

$$\Omega_p = \frac{QB}{m_p}$$

and gyroradius:

$$\rho_p = \frac{v_\perp}{\Omega_p}.$$ 

(5.2)

Based on the good agreement between the observed and estimated values, the observed rotational direction about the magnetic field lines, the linear scaling of the rotational frequency and orbital radius with magnetic field and the close match between the centripetal and magnetic forces, they conclude that the particles under consideration are magnetized.

In our experiment, we do not apply any external magnetic field. However, we did consider that the orbiting can be due to a non-intended external magnetic field (for example the Earth magnetic field $B = (0.3 - 0.6) \times 10^{-4}T$ or contamination by a magnetic field of another experimental set-up). If we assume that the mechanism of the rotation is due to the azimuthal component of the ion drag force as in [77–80], we would expect that this force will have effect not only on several particles but on the whole dust cloud.

If we assume that the orbiting particles are magnetized (for example, different material with higher magnetic relative permeability) we can estimate the gyrofrequency $\Omega_p$ and gyroradius $\rho_p$ as in [81]. Let us assume that the magnetized particle has radius $r_{m,p}$ and material density $\rho$ equal to that of the melamine formaldehyde particles we inject in the plasma, i.e. $r_{m,p} = 4.9 \times 10^{-6} \mu m$ and $\rho = 1514kg/m^3$. This gives charge of the order of 10000 elementary charges and mass $m_p = 7.5 \times 10^{-13}kg$. This results in the following scaling of the gyrofrequency to the magnetic field

$$\Omega_p = 2 \times 10^{-3}B.$$  

In order to explain the observed orbiting as gyromotion even for the lowest observed frequency of $0.2 rad/s$ we would need magnetic field of the order of $100T$, which is not realistic.

Apart from the above arguments, the observations of simultaneous orbiting of two particles (with approximately the same radius and angular velocity) in opposite directions exclude explanation of the orbiting with magnetic field effects.

### 5.4.2 Experiments with vortex-like dust orbiting

There have been several publications [92–95] reporting on rotation of dust particles and convective vortex motion in the absence of a magnetic field. In
some of them, the rotation is induced by a biased probe [92] or by an additional electrode [94]. The rotation in all of these articles has been attributed to the dust charge gradient. Most of the observed rotations have been in the vertical plane and only Samarian et al. [94] report horizontal dust vortices induced by a pin electrode. Agarwal et al. [95] report rotation in the sheath region of a DC glow discharge and note explicitly that the angular velocity of the rotation in the vertical plane is not uniform.

If we compare our results with the other observations of circular motion in absence of magnetic field [92–95], we see several major differences. First, the motion we observe is not vortex-like but orbit-like. Secondly, the orbiting of particles in two opposite directions does not agree with an explanation using spatial variation of the dust charge, due to gradients in plasma parameters (density, electron temperature etc.). Thus, a different mechanism is necessary to explain the orbiting of the particles in our case.

5.4.3 "Frictionless" motion of dust particles

Recently, Annaratone and Morfill [27] have published a work on the motion of particles in the absence of external forces. They report experimental evidence on "frictionless" motion of dust particles in several different set-ups, in particular:

- the Oxford reactor [92] with injected mono-disperse polymer-coated graphite particles;
- the GEC reactor in Garching (e.g. [85]) with injected mono-disperse spherical and elongated particles;
- the PKE chamber (described in [96]) with elongated particles.

Due to the similarities between these experiments and our observations, we will discuss them in more detail later in section 5.5.4.

5.5 Behavior of particles with a different level of symmetry in the plasma sheath

5.5.1 Spherical particles

Let us consider a spherical particle moving in the plasma sheath. Even if we do not consider the particle as a point, the high symmetry does not give any possibility for a force in the azimuthal direction. The only possible
asymmetry in horizontal direction can be due to the radial asymmetry of the electric field dependent forces, i.e. the electrostatic and the ion drag force. However, as these forces can be asymmetric only in radial direction, it is still impossible to find a reasonable explanation of the azimuthal movement of a hypothetical spherical particle unless it has initial speed in this direction.

Let us consider a particle with initial speed in azimuthal direction, due to, for example, the momentum transferred to it during the injection. In section 5.3.2 we have calculated the neutral drag force for a MF particle with diameter $9.8\mu m$ and speed of $16mm/s$ in argon plasma at pressure $18.5Pa$ and temperature of the neutrals $300K$ and obtained a value of $2 \times 10^{-13} N$. If there were no driving force, this neutral drag force would stop the particle, respectively, after $0.02s$. We have observed the orbiting in some cases for more than $10 minutes$. Obviously, driving force is present. The conclusion is that a spherical particle can not orbit. Thus, the particles we have observed as orbiting must be non-spherical. Further we will discuss particles with different level of asymmetry.

5.5.2 Rod-like particles

There have been experimental investigations on rod-like nylon particles in plasma [84, 85]. In them, rod-like particles have been injected in dc [84] or RF plasmas [85]. In the experiments in RF plasma, two particle orientations have been observed - horizontal and vertical. The short particles ($L < 0.37mm$) were levitating vertically, while the long ones ($L > 0.37mm$) horizontally. In our experimental set-up, we have performed experiments with the same nylon particles like in [84, 85]. The $300\mu m$ rod-like nylon particles appeared visibly elongated. At equal magnification, the particles we are discussing in this chapter appear often as points on the screen. Thus, they are significantly smaller than the particles in the experiments of Annaratone and Molotkov. Based on this comparison, we can assume that if the orbiting particles discussed here were rod-like, they would levitate vertically.

Based on the published experiments with rod-like particles [84, 85], Ivlev et al. have build a theoretical model [97]. As we know, if we put a conductor in an external electric field, the charges in it are redistributed. This leads to the induction of a dipole moment $d$. The electrons on the surface of the particle are repulsed by the negatively charged RF-driven bottom electrode. In our case, this leads to a larger charge on the top of the particle (see figure 5.10). Assuming a "weakly inhomogeneous field" (the field variation spatial scale $l_E$ is much longer than the rod $L$):
\[ l_E \equiv \left| \frac{E_0}{E_0'} \right| \gg L, \]

the linear charge density is given by:

\[ \lambda(z) = \lambda_0 + \frac{E_0 z}{2 \Lambda}, \quad (5.3) \]

where \( \lambda_0 < 0 \) is the charge density in the center of the particle (or the constant linear charge density, which the particle would have in absence of electric field), \( E_0 \) is the electric field in the center of the particle, \( z \) is the longitudinal particle coordinate and \( \Lambda = \ln \left( \frac{L}{a} \right) \) is a parameter characterizing the elongation of the particle.

In their article [97], Ivlev et al. show that for a rod-like particle (assuming that the particle charge does not depend on the particle orientation) the only two possible stable orientations are vertical and horizontal, dependent on the so-called “orientation parameter” \( K \), which in fact represents the ratio between the dipole moment \( d = \frac{E_0 L^3}{24 \Lambda} < 0 \) and the quadrupole moment \( D = \frac{QL^2}{6} < 0 \):

\[ K = \frac{2d}{D}. \quad (5.4) \]

The dipole moment turns the particle in the direction of the electric field (in our case, vertical) and the quadrupole moment turns it perpendicularly (in our case, horizontally). The theoretical levitation orientation of the particles is opposite to the one in the experiment. This discrepancy is ascribed to the assumption made in the theory that the particles have a constant charge independent of their orientation. In the same article [97], the authors show that the particle potential and charge depend on the particle orientation.

Further, we will consider that our hypothetical rod-like particle is vertically oriented in agreement with the experiment [85]. In this case, the ion bombardment on the particle would be symmetric from all the sides. Even if we take into account the inhomogeneity in the ion flow, due to the depression in the electrode, it would act in radial direction. Thus, it can not induce movement in azimuthal direction for this type of particles.

### 5.5.3 Flexible particles

If the particle under consideration is a coagulation of spherical particles, we can assume that the force between the separate particles is not very strong. Then it is probable that the particle is flexible.
Figure 5.10: Schematic representation of the charge distribution on a vertical rod-like particle in the electric field of the sheath

Let us see how the field and fluxes would act on a flexible string-like particle in the sheath.

We drop the dust particles in the bulk plasma at about 2 cm height above the electrode. If we estimate the time of falling in the bulk plasma (taking into account only the gravity), we obtain $t_{\text{fall}} = 0.04s$. This time is a lot larger than the charging time $t_{\text{charging}} = 5 \times 10^{-7}s$, estimated roughly from the formula for charging time of a spherical particle in the case of $T_e \gg T_i$ (formula 2.34 in Chapter 2). For this estimation we have assumed a particle diameter of $9.8 \mu m$ in argon plasma with gas density of $5 \times 10^{15}m^{-3}$ and $T_i = 300K$. From formula 2.34 we see that a larger radius of a spherical particle results in a shorter charging time. We assume that in the case of non-spherical particles this trend (larger particles get charged faster) is also valid. Then the calculated charging time for a spherical particle is an upper estimate for the charging time of a larger and non-spherical particle. In conclusion, we can assume that the particles are already charged before reaching the sheath, i.e. in the bulk plasma where we do not have strong electric fields. The charges in the particle will spread away from its center, the two edges will have then excess of charges in comparison with the middle of the particle as shown in figure 5.11(a).

In the plasma sheath, the electric force on the particle ends will be larger than the electric force acting on the middle of the particle. At the same time the gravitational force is acting homogeneously on the particle. This will bend the particle. So, the form of a flexible particle in the sheath would be bent with the ends of the particle higher than the center. This is the usually observed form of big paper fiber particles in the sheath, levitated in the plasma (see figure 5.12).
For a homogeneous ion flux, the ion drag force acting on a flexible bent particle in a steady position is symmetrical on the particle. Changes in the ion drag force (by changing the power and, respectively, the ion density) will only change the levitation height and the curvature (i.e., the angle between the two ends of the particle). An asymmetry in the ion drag force on the particle would be in the radial direction. This can not give momentum in the tangential direction, which is necessary for the orbital motion. Dependent on the position of the bent particle with respect to the radial direction, such an asymmetry can be responsible for spinning of the dust particle, which indeed has been observed.
Figure 5.12: A picture of bent paper fiber particles. The particles are trapped in low-pressure argon radio frequency plasma.

5.5.4 Irregularly shaped rigid particles

If the particle is a rigid body, it is considered that the plasma does not have any effect on its form (effects from asymmetric coating or etching are neglected). A particle created by agglomeration of spherical particles can have any form. The charge is concentrated on the particle surface.

A theoretical example of an asymmetric particle has been discussed in the recent paper of Annaratone and Morfill [27]. The hypothetical particle has a drop-like shape, consisting of a small hemisphere, a conical part and a big hemisphere (see figure 5.13). The charged particle is surrounded by ions and electrons. It creates in its near neighborhood electric fields (the sheath around the particle). Thus, the forces acting on its surface are due to these three components (electrons, ions and electric fields). In the article of Annaratone, the forces due to

- electron pressure:

\[ F_{e,\text{pressure}} = \frac{1}{2} n_e e^{-e V_f / k T_e} \pi r^2 4 \pi r^2; \] (5.5)

- ion bombardment:

\[ F_i = \pi r^2 m_i \sqrt{2 e V_f / m_i} n_e e^{-e V_f / k T_e} \sqrt{k T_e / 2 \pi m_e}; \] (5.6)

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- Maxwell stresses:

\[ F_{\text{Maxwell}} = \oint \varepsilon_0 E^2 \frac{ds}{2} \]  

are considered. Here \( n_e \) is the electron density in the plasma, \( V_f \) - the floating potential of the particle, \( T_e \) - electron temperature, \( e \) - electron charge, \( k \) - the constant of Boltzmann, \( r \) - particle radius (i.e. small or large hemisphere radius), \( m_i \) - argon ion mass, \( E \) - electric field at the surface of the particle, \( \varepsilon_0 \) - vacuum dielectric constant.

![Figure 5.13: Shape of the theoretical asymmetric particle analyzed by Annaratone and Morfill [27]. The plasma sheath thickness depends on the floating potential. The arrows show the direction of the ion bombardment and of the electron pressure.](image)

The forces are calculated at the different walls, assuming different floating potential on the different walls of the particle: for the two hemispheres following the article of Kennedy and Allen [98] and for the conical part, approximating it by the floating potential on ten cylindrical elements of different radius [90]. The results of these calculations give motion of the particle in the direction of the small hemisphere.

The calculations performed for a drop-like particle in [27] are made assuming that the particle is in a homogeneous plasma. To explain the orbiting of particles in the sheath we have to take into account also the electrode sheath electric field, and the directed motion of the ions in it. The effect of the electric field on a particle with a drop-like shape will, in principle, induce dipole moment, which will tend to turn the particle in vertical direction, decreasing the energy. In this case, the discussed forces will not result in movement of the particle. They will only have an effect on the levitation height. In conclusion, even though these calculations show possibility of movement of an asymmetric particle with drop-like shape due to its inhomogeneous charging,
this force can not account for the orbiting of the particles in our experimental conditions.

The last case we will consider is a particle with a completely irregular shape, i.e. without any axial symmetry. Having such a particle in the plasma, the chance of having a particle side tilted simultaneously to the horizontal plane and to the radial plane passing through the particle, is very high. As we will see, this orientation is essential for the proposed explanation of the orbiting motion.

5.6 Mechanisms

Here we will discuss two possible mechanisms for the orbital motion of particles in the plasma sheath: sailing-like orbiting and spinning-induced orbiting. The first one assumes particles levitating at an angle to the electric field and the second considers spinning particles.

5.6.1 Sailing

Let us consider a rod in the plasma sheath at an angle to the electric field.

We can assume that the particle in the sheath is not affected by neutral particles’ flow if it is not moving, as the plasma chamber design (see Chapter 3) assures that the neutral gas flow is negligible in the sheath. Thus, we have to take it into account only as frictional neutral drag force.

Figure 5.14: Forces acting on a rod-like particle in the plasma sheath at an angle to the electric field.

The rod-like particle is subject to bombardment from the ions accelerated...
in the sheath electric field. The exchange of momentum between the positive ions and the dust particle results in an ion drag force.

As we have discussed in Chapter 2, the drag force due to the collection of ions by the particle is called the collective drag force and the one due to the Coulomb interaction between the positive ions and the negative dust particle is the orbit force. In the case of spherical particles, the commonly used formula [5] is:

\[
\vec{F}_{\text{drag}}^{\text{coll,orb}} = n_i m_i \sigma_{\text{momentum}}^{\text{coll,orb}} u_i \vec{u}_i.
\] (5.8)

In this formula, it is not taken into account that the ions leave with certain speed the surface of the dust particle, \(u_i\) is the velocity of the impinging ions. This simplification, neglecting the momentum of the leaving particle is allowed and verified in the case of spherical particles.

Taking into account this additional momentum will give in the case of spherical particles or cylindrically symmetric particles aligned with the ion flow just a small additional contribution to the ion drag force. In the case of a rod-like particle tilted with respect to the ion flow, such approximation is not allowed. As the particle is lying asymmetrically in the ion flow, the ions are collected mainly by the top surface. The velocities of the impinging ions and the leaving ones have a different direction. Thus, the formula for the ion drag force has to reflect this fact. The positive ion drift velocity has to be replaced by the

\[
\vec{v}_{\text{in}} \rightarrow \vec{v}_{\text{in}} - \vec{v}_{\text{fin}}.
\]

The ion drift velocity in the sheath is large and we can expect that the ions will not stick but will be scattered by the rod-particle surface. This gives a component perpendicular to the ion flow. Such a horizontal component is present even for slow ions. They would stick to the surface, neutralize and thermalize (i.e. they will acquire Boltzmann distribution at the particle surface temperature) and then leave the surface as atoms in normal direction. This also gives a force component perpendicular to the ion flow direction.

Thus, ion drag force can cause particle movement perpendicular to the flow direction. As this effect is similar to the way a sailing boat moves perpendicularly to the wind, we have called the force - sailing force.

Up to here, we have discussed only the collection ion drag force. As we know, for big particles, the collection impact parameter \(b_{\text{coll}}\) is larger and, in result, the collection ion drag force becomes more important than the orbit ion drag force. For simplicity, we will neglect it.

Assuming the ions neutralize at the surface and leave in normal direction with velocity \(v_i\), we can estimate the net horizontal force for a rod of length \(L\) and diameter \(2a\), positioned at an angle \(\theta\) with respect to the flow.
Orbiting of dust particles ...

The collisional cross section will be \( \sigma_{\text{coll, ion}} = 2aL \sin \theta \) and the horizontal component of the velocity of leaving particles is \( v_i \cos \theta \). Thus, the net horizontal ion drag force is

\[
F_{\text{hor}}^i = j_i m_i v_i \cos \theta 2aL \sin \theta, \tag{5.9}
\]

where \( j_i = n_i u_i \) is the ion flow.

In presence of a background gas, the sailing force is balanced by the neutral drag force. This results in a stationary velocity. The neutral drag force can be estimated by the simplified Epstein expression \([44, 45]\) in absence of a gas flow, using the neutral drag cross section \( \sigma_{\text{neutral}}^{\text{momentum}} = 2aL \cos \theta \):

\[
\overrightarrow{F}_{\text{ND}} = -2aL \cos \theta m_n n_n v_{\text{th},n} \overrightarrow{v}_p, \tag{5.10}
\]

where \( m_n, n_n \) and \( v_{\text{th},n} \) are, respectively, the mass, density and thermal velocity of the neutrals and \( \overrightarrow{v}_p \) is the particle velocity. From the balance of the sailing and neutral drag forces we can estimate the resulting particle velocity.

We assume that:

- the ions hit the particle with the Bohm velocity (in order to calculate lower limit estimate);
- the ions thermalize at the surface (i.e. that the velocity \( v_i \) corresponds to the particle temperature);
- ions and neutrals have the same mass;
- the particle is at angle of \( \theta = 45^\circ \) to the ion flow flux.

It follows that elongated particle tilted with respect to a vertical ion flow will move in the horizontal direction with a stationary velocity \( v_p \) independent of the particle size. We estimate the particle speed for some typical plasma conditions \( n_i = 5 \times 10^{15} m^{-3}; \ n_n = 5 \times 10^{21} m^{-3}; \ v_{\text{th},n} = 300 K \); and \( v_i \) - calculated from the dust particle temperature measured by G. Swinkels [99] in 20\text{Pa}, 30\text{W} argon plasma (see figure 7.22 in [99]). This results in particle velocity

\[
\overrightarrow{v}_p \approx \frac{n_i v_{\text{Bohm}} v_{\text{th,dust}}}{n_n v_n} \approx 2 \text{mm/s}.
\]

This value is within the range of observed velocities, which shows that the mechanism proposed here is a reasonable explanation of the observed phenomenon.

The above explanation is an idealized case. As we already discussed in section 5.5.2 a rod-like particle will be parallel or perpendicular to the electric field. In this case the ion flow can not induce horizontal movement. For a
Figure 5.15: Series of pictures showing an asymmetric particle, which is orbiting, and its reflection on the electrode. The time difference between the presented frames is 9 frames, i.e. 0.15s.
Orbiting of dust particles ...

particle with irregular form, there are walls, which are tilted with respect to the ion flow. Therefore, the sailing effect can occur. In figure 5.15, it can be clearly seen that the particle is not rod-like and that there is large surface, which is tilted with respect to the electric field.

5.6.2 Spinning induced orbiting

Sometimes, the orbiting particles were observed also to spin around their own axis. This suggests that there is a possible connection between these two types of rotation. Let us analyze how the rotation of a particle will effect its translational movement. In order to simplify the problem, we will take the case of a cylindrical particle, which is spinning with angular velocity $\omega$ around its axis.

In order to visualize the ion bombardment and the asymmetry in the ion induced forces on the particle in consideration, in figure 5.16 a velocity diagram of this process is presented.

Figure 5.16: Velocity diagram of the ion bombardment of a spinning cylindrical particle.

We assume that mono-energetic ions bombard the dust particle and their
velocity vector is perpendicular to the axis of the dust particle. Their velocity we denote by $\vec{v}_{in}$. The momentum transferred from the impinging particles to the dust grain in this approximation is equal on both sides of the particle. Here, we assume that the ions recombine at the surface of the particle. After collision, the particles leave the surface with thermal velocity, determined by the temperature of the dust particle. If there were no spinning of the cylindrical particle, the momentum, transferred by the ions leaving the particle surface, on both sides of the particle would be equal. This means the ion drift will push the particle in the direction of the ion flow. This is not dependent on the exact direction of the velocity of the particle leaving the surface, as the horizontal forces on both sides will equilibrate. If the particle is spinning, this movement is introducing asymmetry in the problem. The tangential velocity of the surface is transferred to the leaving ion (or neutral if there is neutralization at the surface). This means that the particles leaving on the left side (see figure 5.16) will have additional velocity in the same direction as the spinning surface. At any particular point, the horizontal component of this velocity depends on the angle between the radius crossing the point and the horizontal plane. This angle we will denote by $\alpha$. The horizontal component of the leaving ion (neutral) is then $v_{hor} = \omega R \sin \alpha$. The force acting on every small strip from the surface $dS = LRd\alpha$ will be:

$$dF_{hor} = j_i n_i \omega R \sin \alpha LRd\alpha,$$

where $L$ and $R$ are respectively the length and the radius of the cylindrical particle and $\omega$ - the angular velocity. Integrating over $\alpha$ from 0 to $\pi$, we obtain the spinning-induced force acting on the particle in horizontal direction:

$$F_{hor} = 2j_i n_i \omega R^2 L.$$  \hspace{0.5cm} (5.12)

The neutral drag force acting on the cylindrical particle will be:

$$F_{ND} = 2RLn_n v_{n,th} v_p.$$  \hspace{0.5cm} (5.13)

At steady state, the forces equate and give constant particle velocity, which is given by

$$v_p = \frac{n_i v_{Bohm} \omega R}{n_n v_{n,th}}.$$  \hspace{0.5cm} (5.14)

We should note that the ion bombardment of the spinning dust particle creates also a torque, which tends to stop the spinning. We have assumed that there is an unknown mechanism, sustaining the spinning motion.

Another restricting condition for the above-proposed mechanism to be able to explain the orbiting motion is that the spinning axis needs to have a component in radial direction.
Considering cylindrical particle with radius \( R = 10\mu m \) and spinning with angular velocity \( \omega = 10\text{rad/s} \), the particle velocity perpendicular to the ion flow with velocity \( v_{\text{Bohm}} \) for \( n_i = 5 \times 10^{15}m^{-3} \), \( n_n = 5 \times 10^{21}m^{-3} \) and \( T_n = 300K \) has a value of
\[
v_p \approx 10^{-6}mm/s.
\]

Obviously, in our plasma conditions, this force is negligible. This mechanism can become important, in the stellar wind, where the ratio between the ion and neutral density \( n_i/n_n \) is large [100].

5.7 Conclusions

We have observed and analyzed the circular motion of dust particles trapped in the plasma sheath. The orbiting particles are positioned below the main particle cloud. We have shown that the driving force for this rotational motion is dependent on the plasma conditions and it increases with both pressure and radio-frequency power. Based on the similar behavior of the ion drag force and the driving force, we conclude that the orbiting is due to the ion wind acting on a non-spherical particle in the plasma sheath. Due to the analogy with sailing we named this force sailing force. The movement of particles perpendicularly to the direction of the electric field can be induced by the ion flow in the sheath only in particular cases of asymmetry of the dust particle. Several different particle shapes are discussed and it is shown that for spherical, rod-like and bent flexible particles, it is not likely to perform orbital motion within the contemporary knowledge. The analysis of a possible connection between the observed spinning and orbiting is also given. From it we can conclude that in the plasma sheath conditions of our experiment this force is negligible. Still, in some circumstances, it is probable that this force plays important role. In conclusion, only the sailing force appears to give a good explanation for the observed orbiting of dust particles in the laboratory plasma sheath.
Chapter 6

Counter-phase oscillations of dust particles

In this chapter an investigation of vertical oscillations of dust particles with different mass excited by power modulation is presented.

6.1 Introduction

Dust particle oscillations have been investigated and reported in many publications [24, 101–106]. They can be used as diagnostics. The particle oscillation in the sheath of a RF discharge has been used as a method to determine the particle charge [30, 107, 108].

The dust particle oscillations in different experiments have been excited by various means:

- by modulating the RF power with a low frequency sine wave [31, 107];
- by positioning a wire, driven by a sinusoidal voltage source, in the vicinity of the particle [22, 30, 101];
- by focusing a modulated laser beam on the particle [29];
- spontaneously excited (self-excited) [109, 110].

Here, new observations of counter-phase oscillations of dust particles in the plasma sheath are presented.
Chapter 6

6.2 Theoretical background

Let us first present some theoretical aspects concerning particle oscillations. Different types of oscillations (linear, parametric and non-linear) will be briefly presented here.

6.2.1 Linear oscillations

In the analysis of the earliest experiments it was assumed that the particle charge is constant and the electric field in the sheath is linear [101]. This approximation works very well in case of small amplitude oscillations. In physics, the equation of motion for a forced damped harmonic oscillator is well known. Assuming oscillations in vertical direction, this equation can be written as:

\[
m \frac{d^2z}{dt^2} + k \frac{dz}{dt} + Dz = F_0 \sin(\omega t),
\]

where \( m \) is the mass of the particle, \( k \) - the damping constant, \( D \) - the "spring constant" of the undamped harmonic oscillator, \( F_0 \) the amplitude of the driving periodic force acting on the particle and \( \omega \) - its frequency.

In equilibrium, the position of the dust particle is determined by the equilibrium of the gravitational force and the electric force (thermophoretic and ion drag force are commonly neglected):

\[
m_d g = Q_d E(z).
\]

In case of vertical oscillations of dust particles in the plasma sheath, the damping is expected to be due to the neutral gas friction and has to be considered too. The excitation force is taken into account as additional force \( F_0 \sin(\omega t) \). The equation of motion becomes:

\[
m_d \frac{d^2z}{dt^2} = -m_d \beta \frac{dz}{dt} - Q_d E(z) + m_d g + F_0 \sin(\omega t).
\]

For small amplitude oscillations it is usually assumed that the dust charge is constant and the electric field depends linearly on the position in the sheath \( E(z) = E_0 + E' z \). For a linearly dependent electric field the potential profile has a parabolic shape. In this case, the particle will perform harmonic oscillations. The resonance frequency can be determined via

\[
\omega_0 = \sqrt{\frac{D}{m_d}} = \sqrt{\frac{Q_d E'}{m_d}}.
\]
where \( m_d \) is the particle mass and \( E' = \partial E / \partial z \) - the slope of the electric field.

From the Poisson equation 2.11 follows that \( E' = \frac{dE}{dz} = e(n_i - n_e)/\varepsilon_0 \).
From here the particle charge to mass ratio can be determined when the plasma parameters are known, as has been done in [28, 29, 107].

6.2.2 Parametric oscillations

In [30], Schollmeyer et al. analyse the parametric oscillations excited by a wire. They assume that the probe bias affects the sheath width. It can also lead to a temporal change of the dust particle charge. In turn, this results in a periodic modulation of the potential well and its resonance frequency. In this case the equation of motion of a dust particle in the oscillating sheath becomes:

\[
\frac{d^2 z}{dt^2} + \beta \frac{dz}{dt} + \omega_0^2 \left[1 + h \cos(\omega t)\right] z = F_0 \sin(\omega t). \tag{6.5}
\]

A parametric oscillation is characterized by the existence of sub- and super-harmonics of the resonance frequency. Also in the presence of damping there is a threshold of the modulation depth in order to excite parametric resonances. In [30] both specific features have been shown to exist for the excitation of oscillations by a wire. They also present a comparison between experimental curves of oscillations excited by wire and by the electrode voltage modulation and show that only the excitation by the wire has parametric resonance at \( \omega_1 = 2\omega_0 \).

6.2.3 Nonlinear oscillations assuming non-linear variable particle charge and/or non-linear electric field

As we know, the ion and electron densities vary in the plasma sheath. Another approach to the nonlinear oscillations is by taking into account these variations. As the dust charge is determined by the ion and electron currents to the particle surface, we can expect a height-dependent dust charge. On the other hand, the assumption of a linear electric field in the plasma sheath is also an approximation.

In order to take into account these non-linearities Zafiu et al. [31] assume that the particle charge and the electric field are described by polynomial functions:

\[
Q(z) = Q_0 + Q_1 z + Q_2 z^2 + Q_3 z^3, \tag{6.6}
\]

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\[ E(z) = E_0 + E_1 z + E_2 z^2 + E_3 z^3. \] (6.7)

That way the equation of motion includes higher order terms:

\[ \frac{d^2 z}{dt^2} + \beta \frac{dz}{dt} + C_1 z + C_2 z^2 + C_3 z^3 = \frac{F_0}{m_d} \sin(\omega t), \] (6.8)

where \( C_1, C_2, C_3 \) are combinations of the electric field and charge coefficients. The three coefficients determine the resonance frequency, the potential asymmetry and the weakening/strengthening of the potential, respectively.

### 6.3 Experimental details

After giving this brief theoretical background of the dust particle oscillation, we can now proceed with our experiment.

Let us first see how the particle oscillations are excited experimentally. The experiments reported in this chapter have been performed in the experimental set-up described in Chapter 3. The difference between this and the other experiments reported in this dissertation is the modulation of the voltage applied to the bottom powered electrode. For these experiments sine-shape amplitude modulation (see figure 6.1) has been used.

\[ V = V_{\text{ampl}}(1 + h \sin(\omega t)), \] (6.9)

where \( V_{\text{ampl}} \) is the voltage amplitude, \( \omega \) the modulation frequency and \( h \) the relative modulation depth.

If we assume that within the modulation power range the plasma impedance is constant and \( P \sim V^2 \):

\[ P = P_{\text{ampl}} \left(1 + 2h \sin \omega t + h^2 \sin^2(\omega t)\right). \] (6.10)

As usually the modulation depth \( h \ll 1 \), we can neglect the last term on the right and then the power modulation can be approximated as:

\[ P = P_{\text{ampl}}(1 + 2h \sin \omega t). \] (6.11)

The particle oscillations have been investigated in the modulation frequencies range between 1\( Hz \) and 40\( Hz \). In this chapter, mainly the low-frequency (1\( Hz \)) modulation will be discussed. The response time of the plasma to electrical changes is well below the modulation period in the experiment. Thus, the reaction of the plasma to the voltage modulation can be considered as immediate.
6.4 Experimental observations of counter-phase oscillation

6.4.1 Counter-phase oscillation of particles with different mass

In this section experiments on oscillations of melamine formaldehyde spherical particles with two different diameters \((4.79 \pm 0.08) \mu m\) and \((9.78 \pm 0.13) \mu m\) will be discussed.

In order to avoid possible side effects from the void formation discussed in Chapter 4, the experiments have been performed at low pressure and low RF power. In particular, the experiments are performed at a pressure of \(8Pa\) and a power of \(1.5W\). The modulation depth of the electrode voltage is \(h = 15\%\), which gives about 30\% modulation depth of the power.

The experiments have been performed for the two different particle sizes, separately. In both cases, the particles form a cloud in the middle of the electrode depression. Several heavier particles - possibly agglomerates, due to the aging of the melamine formaldehyde particles have been observed below the main cloud.
The field of view of the camera has been chosen in such a way that we can observe the particles in the sheath as well as the bulk plasma. This allows us to gain information on the modulation phase of the particles movement with respect to the power modulation phase by tracking the plasma emission.

At low modulation frequencies, the light particles with a diameter of 4.79\(\mu m\) approach the electrode with increasing power and elevate higher above it with decreasing power. These particles levitate at an average level of 5.5\(mm\) above the bottom of the depression in the electrode. At the same time the heavy agglomerate particles behaved in an opposite manner. In figure 6.2 the oscillations of the 4.79\(\mu m\)-diameter particles and of two coagulate particles are presented. The data for the lowest particle are not complete as during the oscillation it goes below the area of observation.

![Figure 6.2: Oscillations of three particles with different size: 4.8\(\mu m\)-diameter particle and two heavier coagulates. The modulation frequency is 1Hz, the pressure 8Pa and the power 1.5W.](image)

The experiment with the spherical particles with diameter 9.78\(\mu m\) verified that the behavior is determined by the mass and not by the irregular shape of the agglomerate particles, as discussed in Chapter 5. The 9.78\(\mu m\)-diameter particles levitated at level of about 4.9\(mm\) above the bottom of the electrode depression. This is also approximately the height of coagulate 1 in figure 6.2. These heavy particles move higher in the sheath with increasing power and go deeper in it with decreasing power. The observation of these oscillations
Counter-phase oscillations of dust particles

agrees with the intuitive thought that an increasing power and an increasing electric field will lift a particle in the sheath as well as with the observed trend in the vertical position of particles with power in the range of higher powers, shown in Chapter 4 in figure 4.4.

In order to study the anomalous behavior of the 4.8µm-diameter particles, the resonance curves of the two particles are analyzed and compared below.

In figure 6.3 a graph of the measured oscillation amplitude as function of modulation frequency for the 4.79µm-diameter particle is presented. The resonance frequency is found to be \( \nu_0 = 26.5 \pm 0.5 \text{Hz} \). A small resonance peak at \( \nu = 13 \pm 1 \text{Hz} \), which corresponds to \( \nu_0/2 \) is observed too. The presence of this superharmonic resonance (resonance at integer fraction of the fundamental frequency) shows that the particle oscillates nonlinearly. Superharmonic resonance has been observed earlier in experiments on excitation of vertical particle resonances by laser radiation pressure and by square wave modulation of the electrode voltage [29]. In those experiments dependent on the conditions additional resonances at \( \nu_0/2, \nu_0/3, \nu_0/4 \) have been observed. The observation of the \( \nu_0/2 \) resonance indicates that the potential well, in which the particle oscillates is not symmetric.

![Figure 6.3: Amplitude of the modulated oscillations of 4.8µm particles as function of the modulation frequency. The pressure is 8Pa and the power 1.5W.](image)

In figure 6.4, the oscillation amplitude as a function of the modulation frequency for the large particles (diameter 9.8µm) is given. For these parti-
cles, the resonance frequency is $\nu_0 = 16 \pm 1 Hz$. A second resonance has been found at $\nu = (33 \pm 1) Hz$, which is in fact $2\nu_0$, i.e. a subharmonic resonance.

![Image of modulated oscillations](image)

Figure 6.4: Amplitude of the modulated oscillations of 9.8µm particles as function of the modulation frequency. Two resonances are clearly visible- the fundamental at $\nu_0 = 16 \pm 1 Hz$ and a secondary one - at $\nu = (33 \pm 1) Hz$. The pressure is $8 Pa$ and the power $1.5 W$.

As we have mentioned earlier in this chapter, in the article of Schollmeyer [30], a comparison between the resonance curves due to excitation by modulation of the voltage on the lower electrode and by wire excitation is presented. It has been show that a second resonance at double frequency can be excited only by the wire but not by the voltage modulation. Our experiment shows that this is not true for all the experimental conditions. A difference between the two experiments is the RF power supplied to the plasma. The difference in the power is almost an order of magnitude ($11 W$ in [30] versus $1.5 W$ in our experiment). As we have shown in our experiment, the increasing power results in movement of the levitated particles in opposite directions. In an imaginary experiment with two different size dust species the increase in power would result in vertically denser cloud. In terms of electrical features of the sheath, assuming constant charge of the dust particles, this would mean a larger gradient of the electric field. Moreover, this results in narrowed potential well. This can explain the lack of observation of second resonance in [30] and its presence in our experiment. As there is no
information on the modulation depth in [30], a comparison of this parameter is not possible. If the modulation depth in [30] is smaller than \( h = 15\% \), which is the modulation depth in our case, this can as well be reason for the discrepancy between the two experiments.

In figure 6.5, the upwards and downwards extreme positions of the 9.8\( \mu \)m-diameter particles (with respect to the equilibrium position) during oscillations as function of the modulation frequency are shown. Within the experimental error, the upwards and downwards branches of the amplitude curve appeared symmetric.

![Graph showing the highest and lowest position of the oscillating 9.8\( \mu \)m particles above the electrode as function of the modulating frequency. The 0 corresponds to the equilibrium position of the particle. No asymmetry in vertical direction is observable.](image)

**Figure 6.5:** Highest and lowest position of the oscillating 9.8\( \mu \)m particles above the electrode as function of the modulating frequency. The 0 corresponds to the equilibrium position of the particle. No asymmetry in vertical direction is observable.

Analogically, in figure 6.6, the highest and lowest position with respect to the equilibrium level of the oscillating 4.8\( \mu \)m-diameter particles as function of the modulation frequency is presented.

At low frequencies these particles are affected by oscillations of heavier particles. In order to avoid this side effect, the range below 26Hz is not analyzed. In the range above 26Hz a clear asymmetry upwards in the region of large amplitudes is visible. This agrees with the observation of second resonance in figure 6.3.
Figure 6.6: Highest and lowest position of the oscillating 4.8\(\mu\)m particles above the electrode as function of the modulating frequency. The 0 corresponds to the equilibrium position of the particle. The asymmetry in the region of large amplitude oscillations is clearly visible.

6.4.2 Observation of particles not affected by the modulation

Counter-phase oscillations have been observed also in a different experiment using cylindrical particles. It appeared that above the cloud of cylindrical particles there was a cloud of lighter particles. The particles are assumed to be debris particles, i.e. pieces of broken cylindrical particles.

While applying modulated RF power on the bottom electrode, the particles did not oscillate in phase. The cylindrical particles were oscillating in phase with the power, i.e. they were in the highest position when the power was reaching its maximum.

Within the debris cloud there were particles oscillating in phase with the plasma sheath edge as well as in counter-phase. The latter were the particles in the upper part of the cloud. A series of five frames, representing one period of the oscillations, is shown in figure 6.7. In this particular case, the RF power is oscillating in the range 10-11W. A remarkable feature of this series of pictures is that it does capture counter-phase oscillation of two particles as well as a particle, which position is not influenced by the modulation of
the electrode potential within the experimental error.

![Series of pictures](image-url)

Figure 6.7: Series of pictures, representing a cycle of the induced oscillations (1Hz) in the power range 10 – 11W. The pressure is 16Pa. Three particles levitating at different height are visible. While the two particles on the right oscillate in counter-phase to each other, the particle on the left is in approximately stable position.

In figure 6.8 a graph of the relative height of the three particles from figure 6.7 during 5 oscillation periods is given. In this graph it can be noticed that the middle particle is (within the experimental error) in a stable vertical position.

![Graph](image-url)

Figure 6.8: Time dependence of the particle height in 5 cycles for the three particles visible in figure 6.7. Within the experimental error the middle particle does not oscillate.

This experiment proves that there is a position in the sheath, at which the particles do not feel the periodic modulation of the electrode potential.
6.5 Analysis of the counter-phase oscillations

6.5.1 Estimate of the phase shift between the oscillations and the driving force

The phase of a forced harmonic oscillator in the limit of $\nu \to 0$ is identical with the phase of the driving force. At resonance, the phase difference is $90^\circ$ and at high frequencies the phase difference approaches $180^\circ$. As we have seen in figures 6.3 and 6.4 the resonance frequencies for the 4.8$\mu$m and 9.8$\mu$m are 26.5Hz and 16Hz, respectively. Thus, we conclude that in the observation of the counter-phase oscillations, both particles are in phase with the driving force of the oscillation.

6.5.2 Analysis of the equation of motion for the particle not affected by the modulation

Since the driving force changes direction as function of height, we consider that it consists of two counteracting forces.

The position $z$ of a particle in the sheath is determined by the force balance:

$$m_d \frac{d^2z}{dt^2} + F_i(z) = F_{el}(z).$$

Indeed the ion drag force counteracts the electrostatic force but the gravitational force is large for the particles under consideration. From equation 6.12 as well as from table 2.2 in Chapter 2 it is clear that $F_{el}(z) \gg F_i(z)$ and the ion drag force cannot play an important role for the particle oscillations.

Therefore, we can state that the appearance of counter-phase oscillations is due to a peculiarity of the electrostatic force acting on the dust particles in the plasma sheath.

Neglecting the ion drag force and taking into account that the driving force of the oscillations can be simply implemented in the electrostatic force, as the electrode power is modulated, the equation of motion becomes:

$$m_d \frac{d^2z}{dt^2} + m_d\beta \frac{dz}{dt} = m_dg - Q_dE(z,t).$$

As mentioned earlier, there is a position $z$, in which a particle will not be influenced by the oscillating plasma parameters. In this case, $\frac{d^2z}{dt^2} = 0$ and $\frac{dz}{dt} = 0$. Assuming constant particle charge, the electric field can be expanded as:

$$E(z,t) = E_0 + \frac{\partial E}{\partial P_{RF}} \frac{dP_{RF}}{dt} dt + \frac{\partial E}{\partial z} dz.$$
Counter-phase oscillations of dust particles

For a dust particle at a stable position the last term vanishes \((dz = 0)\). In order to describe the stable position of the particle despite the power modulation, the term \(\frac{\partial E}{\partial P_{RF}} \frac{dP_{RF}}{dt}\) in equation 6.14 has to be invariant of time. This is true only if at this position in the plasma sheath

\[
\left. \frac{\partial E}{\partial P_{RF}} \right|_z = 0. \quad (6.15)
\]

### 6.5.3 Sheath model

In order to check the existence of a position in the sheath, for which the condition 6.15 holds, a plasma simulation has been performed.

The electric field profile in the plasma sheath is calculated using the self-consistent numerical fluid model of M. Kushner. As we have seen in Chapter 4, this model is very suitable for the region of the plasma sheath. As the observed counter-phase oscillations are at low frequency, we can assume that at every moment the particles are in quasi-equilibrium with the plasma. Therefore, the plasma simulation has been performed for two different powers, corresponding to the minimum and maximum power during the power modulation in the experiment, respectively 10 and 11 W. The pressure is 16 Pa. The profile of the electric field above the electrode for these two powers is given in figure 6.9. It can be clearly seen that in the sheath there
is a point, at which the two curves cross. This shows that there is a level above the electrode, at which the electric field does not change with power within the power range $10^{-11} W$.

At $z < z_0$, i.e. below the level, at which $\left.\frac{dE}{dP_{RF}}\right|_{z_0} = 0$, the electric field increases with power. Therefore, particles levitating at $z < z_0$, will oscillate in phase with the power. At $z > z_0$, the electric field decreases with power. Particles levitating at such position will oscillate in counter-phase.

### 6.6 Conclusions

We have observed for the first time counter-phase oscillations of dust particles with different sizes in the plasma sheath. This indicates that there must be a position, at which a particle will not feel the modulation of the electrode potential. In an experiment with cylindrical particles, this intuitive conclusion (based on the principle of continuity) has been verified. We have indeed observed a particle, which does not react to the oscillating field. In order to get insight in the cause of this invariant behavior, the plasma has been simulated via the self-consistent fluid model of M. Kushner, discussed in Chapter 4. It appeared that the counter-phase oscillations follow also from the model. The analysis of the oscillations together with the results of the model show that the counter-phase oscillations are due to a peculiarity of the electric field in the plasma sheath: there is a position, at which the electric field is constant as function of power. In this way, the particle kinetics can be useful for studying sheath structure and validating numerical models.
Chapter 7

Overview and conclusions

This dissertation is dedicated to investigation of various newly discovered phenomena, occurring in the plasma sheath of low-pressure capacitively-coupled dusty plasmas: voids, orbital motion of isolated particles and driven counter-phase oscillations.

In dusty plasmas, a "void" is called a dust-free region in the dust cloud levitated in the plasma. Such effect can be observed in the bulk plasma as well as in the plasma sheath. The aim of a part of this dissertation is to investigate voids, created in the plasma sheath. The void dependence on pressure and RF power is investigated. Langmuir probe measurements above the electrode depression have shown that the profile of the electric potential gets flatter with power and at high enough pressures a dip in the middle appears. Two models concerning the dependence of the cloud size on pressure and RF power are explained. The first one - phenomenological - is fitting quite well the trend in the void development with pressure and power. The second one - the surface tension theory - shows that there are conditions, in which the surface tension in a void is larger than the surface tension in the cloud. These two models do not propose a driving force for the void formation. In order to find the source of void formation, two plasma-dust numerical simulations based on a fluid model have been performed for our experimental conditions. Their results differ substantially. Via analysis of the differences between the two models, it is concluded that the radial component of the ion drag force is the most probable driving force for void formation.

In the second part of this thesis, we have observed and analyzed circular motion of dust particles trapped in the plasma sheath. Analyzing several features of this movement (relative particle position, velocity dependence on RF power and velocity dependence on gas pressure), a similarity between the driving force and the ion drag force has been discovered. It is assumed that
the orbiting is due to the ion wind acting on a non-spherical particle. This force is called "sailing force" and its mechanism has been explained. It has been shown that an orbiting movement can take place only for non-spherical particles. A mechanism based on the spinning observed in several cases of orbiting particles has been proposed. After analysis it is concluded that such effect is negligible in the our experimental conditions. In conclusion, the "sailing force" appears to be the only explanation for the observed orbiting of dust particles in the plasma sheath.

The third major part of this thesis is dedicated to another new phenomenon - counter-phase oscillations of particles with different size. In this experiment, the electrode voltage is modulated. Heavier particles are elevated and the lighter ones are lowered with power. This indicates that there is a position, which is not affected by the modulation of the electrode potential. In an experiment with particles with unknown size distribution, such a position has been observed. A plasma-dust simulation has been performed based on the model successfully describing the void formation. The counter-phase oscillations follow also from the model. After analysis, the counter-phase oscillations have been attributed to a peculiarity of the electric field in the plasma sheath: the presence of a position, at which the electric field is constant as function of power.

In conclusion, the work performed in this thesis gives insight in several newly observed phenomena in dusty plasma and via them also on the electric field profile in the plasma sheath and the importance of the ion flow in it.
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Summary

In the last decades dusty plasmas have attracted a lot of attention from different fields. The astrophysics is interested in them as dust is present in many astrophysical environments, e.g. interstellar medium, nebulae, comet tails and planetary rings. On the other hand, plasmas are used in many industrial applications. While for the microelectronics industry the dust appearance in the plasma is unwanted, in the solar cells industry or the catalyst production, dusty plasmas have positive aspects. Dusty plasmas are of fundamental interest not only in the astrophysics. For example, Coulomb crystals are attractive model systems for solid-state crystals. The particle-plasma interaction is also used as a diagnostic tool for the characterization of the electric field profile in the plasma sheath.

In typical laboratory dusty plasmas, micrometer-sized particles are negatively charged and levitated in the plasma sheath. There, a dust particle is subject to many forces. This makes their dynamics quite complicated and this results in many interesting phenomena. In this thesis the mechanisms of several sheath phenomena in dusty plasma are explained.

The experiments presented in this thesis are performed in a low-pressure capacitively-coupled RF plasma in argon. The sheath phenomena observed, in particular, are: voids, orbiting of isolated particles and driven counter phase oscillations of particles with different mass.

In dusty plasmas, a void is called a dust-free region in the dust cloud levitated in the plasma. Voids have been observed both in the bulk plasma and in the plasma sheath. Part of this thesis investigates 2D-voids developing in a dust cloud of 9.8μm-diameter particles levitating in the plasma sheath. The void size is found to increase with both power and pressure. The effect of the size of the trapping depression is also investigated. For our experimental conditions, no voids are observed above a small diameter (1cm) depression. The cloud-volume dependence on pressure and power is addressed by a phenomenological model. It fits well the trend in the void development with pressure and power. Another theory - surface tension theory - has shown that at certain conditions the surface tension in a void is larger.
than the surface tension in the cloud around it, which makes the void stable. These two models do not address the driving force for the void formation. Therefore, two plasma-dust numerical fluid models have been applied to our experimental conditions. One of them shows a discrepancy with the experiment, while the second agrees with it. After analyzing the differences in the physics included in the two models, the radial ion drag force appears the major possible reason for void formation.

The second phenomenon discussed here is orbital motion of individual particles trapped in the plasma sheath. As these particles are positioned below the main dust cloud of spherical particles, it is assumed that these particles are non-spherical coagulates. Their velocities increase with pressure and power. Some of the orbiting particles are also spinning. The observed orbiting has been compared to other experiments, in which similar effects have been induced, and it is proven that the mechanism of the orbiting in the actual experiment is different from the proposed mechanisms in the literature. It is shown that a symmetric particle can not perform orbiting motion. Due to the similarity between the unknown driving force and the ion drag force, it is suggested that the orbiting is due to the ion wind acting on a non-spherical particle. The sailing mechanism appears the best explanation for the orbiting of dust particles in the plasma sheath.

The third new phenomenon described and explained in this thesis is counter-phase oscillations of particles with different size. By modulating the electrode voltage, particle oscillations are investigated. Two different sized particles are used: $4.8\mu m$ and $9.8\mu m$. The particles oscillate in counter phase. Furthermore, a position where particles are not affected by the modulating electrical field has been found. This is corroborated by model results, showing that there is a position in the sheath where the electrical field is constant with changing plasma power. The particles levitated below this level move upwards with increasing plasma power, while those trapped above this level move downwards.

Based on the work performed in this thesis, we can conclude that the ion drag force on particles in the plasma sheath is negligible for phenomena occurring in the vertical direction, in which also the large gravitational and electrical forces act, but it is responsible for some interesting phenomena in the horizontal direction.
Samenvatting

In de laatste decennia hebben stoffige plasma’s veel aandacht van diverse onderzoeksvelden getrokken. De sterrenkunde is geïnteresseerd in stoffige plasma’s, omdat in veel astronomische omgevingen, zoals de interstellaire ruimte, nevelvlekken, komeetstaarten en planetaire ringen, stof aanwezig is. Uit fundamenteel oogpunt zijn stoffige plasmas niet alleen in de sterrenkunde van belang. Coulomb kristallen zijn aantrekkelijke model systemen voor vaste stof kristallen. De interactie tussen plasma en stofdeeltje wordt verder gebruikt voor de karakterisering van het elektrische veldprofiel. Plasma’s worden ook gebruikt in veel industriële applicaties. Terwijl in de micro-elektronica industrie stof in het plasma ongewenst is, hebben stoffige plasmas positieve aspecten in de productie van zonnecellen en katalysatoren.

In typische laboratorium plasma’s worden de stofdeeltjes met een diameter in de orde van grootte micrometers negatief geladen en zweven ze in de plasma grenslaag. Op een stofdeeltje werken verschillende krachten. Dit maakt hun dynamica complex, zodat er een grote verscheidenheid aan verschijnselen ontstaan. In dit proefschrift worden de mechanismen van enkele van deze verschijnselen in de grenslaag van een stoffig plasmas nader bestudeerd.

De experimenten zijn uitgevoerd in een lage druk capacitief gekoppeld radiofrequent argon plasma. De drie verschijnselen in de grenslaag, die worden beschreven zijn: "voids", rotatie van sommige individuele stofdeeltjes en oscillaties van deeltjes met verschillende massa.

Een "void" in een stoffig plasma is een stofvrij gebied binnen de stofwolk in het plasma. "Voids" worden waargenomen, zowel in het plasma volume, als in de grenslaag. Dit proefschrift onderzoekt 2D "voids" die ontstaan in de stofwolk van stofdeeltjes met diameter van 9.8 $\mu m$ zwevend in de plasma grenslaag. De void diameter groeit met het vermogen en de druk. Verder blijkt de electrode geometrie van belang te zijn voor de vorming van een "void". Zo ontstaat er geen "void" als de wolk in een te kleine ruimte wordt opgesloten. De afhankelijkheid van het wolk volume van vermogen en druk wordt geanalyseerd met behulp van een fenomenologisch model. Het
model geeft de trend in de ontwikkeling van de void met druk en vermogen goed weer. Een alternatief model - gebaseerd op oppervlaktespanning - laat zien dat onder sommige omstandigheden de oppervlaktespanning in een void groter is dan de oppervlaktespanning binnen de stofwolk. Dit maakt een "void" stabiel. Beide modellen behandelen niet het ontstaan van de "void". Om dit te begrijpen, worden twee numerieke vloeistof modellen aan onze experimentele omstandigheden aangepast. Slechts een model reproduceert de experimentele resultaten. Omdat het belangrijkste verschil in de modellen de aanwezigheid van een radiële ionen drift is, concluderen we dat dit verantwoordelijk is voor de "void" vorming.

Het tweede onderwerp is de cirkelvormige beweging van individuele deeltjes in de plasma grenslaag. Deze deeltjes zweven lager dan de hoofd stofwolk van sferische deeltjes. Daarom is het waarschijnlijk dat deze deeltjes asymmetrische conglomeraten van de sferische deeltjes zijn. Hun snelheid neemt toe met druk en vermogen. Sommige van deze deeltjes roteren ook nog om hun eigen as. Na een analyse van de literatuur blijkt dat alle tot nu toe voorgestelde rotatie en translatie mechanismen onze waarnemingen niet kunnen verklaren. We laten zien dat een sferisch deeltje niet in staat is om onder onze condities een cirkelvormige baan te beschrijven. Op basis van de waargenomen trends concluderen we dat onze deeltjes niet-sferische deeltjes zijn die door de ionen wind worden aangedreven.

Het derde verschijnsel dat we bekijken is de oscillatie van deeltjes met verschillende massa, via modulatie van de elektrodespanning. Deeltjes met verschillende diameter (4.8\(\mu\)m en 9.8\(\mu\)m) worden gebruikt. De deeltjes oscilleren in tegenfase. Bovendien is er een positie, waar de deeltjes niet bewegen ondanks de modulatie van het elektrische veld. Dit wordt ondersteund door de resultaten van een model, dat laat zien dat er een positie in de grenslaag bestaat waar het elektrische veld constant is bij een variërend plasma vermogen. De deeltjes zwevend onder dit niveau gaan omhoog met toenemend plasma vermogen terwijl de deeltjes erboven naar beneden bewegen.

Op basis van dit proefschrift concluderen we dat de ionen drift in de plasma grenslaag verwaarloosbaar is voor het gedrag van deeltjes in de verticale richting, waarin ook de relatief grote zwaarte- en elektrische krachten werken. De ionen drift veroorzaakt echter wel vele interessante verschijnselen in de horizontale richting.
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