Investigations of dust in a laboratory plasma

Tommy Johansson

Division of Plasma Physics
Alfvén Laboratory
Royal Institute of Technology
SE–100 44 Stockholm, Sweden
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Abstract

An investigation of spherical anode plasma is presented. The plasma, also known as a fireball, was found to have two modes, called "sharp" and "diffuse".

The difference between the two modes was investigated, and found to be temporal oscillations in the diffuse mode, as the fireball was turned on and off rapidly. The cause of the oscillations is a negative differential resistance associated with a double layer at the edge between the spherical anode plasma and the background plasma.

Further, the effects of dust grains on the fireball were investigated. The dust consists of grains of aluminium oxide with a size of 1 or 5 μm. No effect from the larger grains is found. For the smaller grains, it is found that the periods of extinction in the diffuse mode become longer. This work is intended as an initial study in preparation for future dusty plasma experiments.
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1 Introduction

*Dusty plasma* is a relatively new area in plasma physics. The field has received increasing attention over the last decade. At the Alfvén-laboratory, KTH, the work on dusty plasmas has recently begun. This Master thesis concerns the diagnostics of a spherical plasma, called a *fireball* by some authors, and the effects of dust on it.

A dusty plasma is a plasma in which not only positive ions and electrons are present, but also larger particles, dust grains. The size of these grains is typically of the order of μm. There are a number of mechanisms for charging dust particles, such as collisions with ions and electrons and photoionisation. The influence of gravitation may often not be neglected. The grains will float, when the gravitational force and the electromagnetic force are equal in magnitude but opposite in direction.

The properties of the plasma may be strongly altered in the presence of high densities of dust. A plasma, by definition, is considered to be electrically quasi-neutral. To retain the quasi-neutrality also for dusty plasmas, the charge density of the dust must be added to the densities of ions and electrons.

Dust clouds in a laboratory environment have been found to form structures [see for example *Moffat and Thomas* 1996; *Nuomura et al* 1998; *Samarian and Vaulina* 2000]. The term used to describe the ordered state of dust in a plasma, is *plasma crystal*, which is in some sense similar to crystal structures found in metals. Dusty plasmas are common in space, and found e.g. in the tails of comets and in planetary rings to name a few. In particular, dusty plasmas have been shown to be of interest in connection with the rings of Saturn [Goertz 1989; *Northrop 1992, Brenning 2001*]. Dusty plasmas are also important in technological applications, as dust particles are often found to contaminate plasma processes.

The objective of this work was to perform diagnostics on the non-dusty plasma inside and outside the *fireball*, which is the term used for an anode plasma with spherical shape. In addition effects on the plasma caused by dust was searched for. In the plasma tank, where the experiments were performed, there was also a background plasma present. At the boundary between the fire ball and the background plasma, an electrical double layer was assumed to exist, and experiments were designed in order to investigate the characteristics of this layer. The shape of the fireball was in most cases spherical, but in some cases a more ellipoid shape was observed. Two modes of the spherical plasma were observed, one of which was a ball with visually sharp edges, whilst the second had more diffuse edges. The difference between these two modes was of interest.

This work is intended to be a first investigation of the spherical plasma and the effects dust might have on it. An additional objective has been to achieve an overview of the experimental requirements.
2 Theory

Some general properties of dust charging, double layers and negative differential resistance associated with double layers will be discussed in this chapter.

2.1 Charging of dust in plasma

A dust grain in a surrounding plasma accumulates electric charge, most likely a net negative charge since electrons, due to their smaller mass, have higher mobility. This is true only as long as emission of electrons is unimportant. In situations with a high rate of electron emission, the grain attains a positive equilibrium charge. If emission is not dominating, the negative charge of the grain will increase to a point of saturation. Ion and electron currents then will be in equilibrium.

As long as the grain radius is smaller than the Debye length, orbital motion limited (OML) theory may be used. This theory is also useful for electrical probes in plasmas and for spacecraft charging, if the size of the objects is smaller than the local Debye length.

Assuming only Maxwellian electrons and ions, the currents to a spherical grain with radius $a$ are

$$I_e = e \pi a^2 \frac{n_e \nu_i}{\sqrt{2 \pi}} \exp\left(\frac{e\phi}{kT_e}\right) = n_e m_e^2 \left(\frac{kT_e}{2 \pi m_e}\right)^{1/2} \exp\left(\frac{e\phi}{kT_e}\right) \quad \phi_e < 0 \quad (2.1a)$$

$$I_i = z_i e \pi a^2 \frac{n_i \nu_i}{\sqrt{2 \pi}} \left(1 - z_i e \phi / kT_i\right) = n_i z_i e m_i^2 \sqrt{\frac{kT_i}{2 \pi m_i}} \left(1 - z_i e \phi / kT_i\right) \quad \phi_i < 0 \quad (2.1b)$$

for negative surface potential of the grain, $\phi$, relative to the plasma. $T_e$ and $T_i$ are the electron and ion temperatures, $z_i$ is the number of elementary charges of the ions, $n_i$ and $n_e$ are the number densities of the ions. The above equations give the surface potential of a grain if emitted electrons are ignored. When the sum of all currents to the grain is set equal to zero, the surface potential equivalent to equilibrium charge may be determined.

With $C$ the capacitance of the grain, the charge is

$$Q_{d} = C \phi \quad (2.2)$$

The capacitance of an isolated, spherical grain in a plasma may be written [Whipple et al 1985]

$$C = 4 \pi \varepsilon_0 a \left(1 + ka\right) \quad (2.3)$$

where $k^2 = 1/\lambda_D^2$ and $k$ is the reciprocal of the Debye length. The expression above may be written approximately
valid if the grain is much smaller than the Debye length, i.e. \(a < \lambda_D\). Assuming isolated grains, (2.3) and (2.4) give the charge of the grain.

If the grains are not isolated, the average charge will be reduced [Goertz 1989], when the average grain distance is smaller than the Debye length. A parameter to determine whether the charge and surface potential is reduced or not, is Havnes’s value \(P\). For grains of the same radius \(a\), \(P\) is given by [Havnes et al 1990]

\[
P = 659 \frac{T_e a n_d}{n_e},
\]

(2.5)

where \(T_e\) is the plasma temperature in eV, \(n_d\) and \(n_e\) the dust and electron number densities in cm\(^3\) and the radius \(a\) in \(\mu m\). Goeree (1994) gives \(P > 1\) for reduced charge and surface potential and \(P < 1\) for almost no reduction.

Whipple et al (1985) found the potential surrounding an isolated grain to be

\[
\Phi(r) - \bar{\Phi} = \frac{Q \exp[-k(r-a)]}{r} \frac{a}{4 \pi \epsilon_0 (1 + ka)} = \frac{\phi_a}{r} \exp[-k(r-a)]
\]

(2.6)

where \(\bar{\Phi}\) is the average of the potential over the volume containing the plasma. The currents to the grains are driven by the potential difference \(\Phi - \phi_a\). The charge on each grain is now [Goertz 1989]

\[
Q = 4 \pi \epsilon_0 a (\phi_a - V_p)
\]

(2.7)

if \(a < \lambda_D\). \(V_p\) is the maximum potential between the grains. The surface potential will depend on the charge [Northrop 1992].

Photoionization and secondary electrons contribute positive charge to the grain. If the energy of the incoming electron is sufficiently high, secondary electrons are emitted. The yield also depends on the particle material. In addition a positive current to the grain is caused by photoionization, since photoelectrons are released when the grain absorbs UV-radiation.

The main source of UV-radiation in laboratory plasmas are excited neutral atoms and ions. In the experiments described in this work, neutral argon atoms and probably contaminating molecules, like water, are present. By means of electron collisions the neutrals might be excited. When they return to their ground state, UV-radiation is emitted.

To correctly determine the charge, it is important to know the time necessary for a grain to reach equilibrium charge. In the experiments performed for this work, the dust falls by gravity through the plasma and the fireball. The charging time must therefore be comparable to the time of exposure in the spherical plasma. Cui and Goeree (1994) found the charging time to be

\[
\tau = K_r \left(\frac{kT_e}{an}\right)^{1/2}
\]

(2.8)
for an initially uncharged grain. The factor $K_f$ depends on the ion and electron temperature and mass of the ion. The radius of the grain is $a$, $n$ the plasma density and $T_e$ the electron temperature. Larger grains reach equilibrium charge faster than small ones. High plasma density decreases the charging time. $K_f$ was determined numerically by Cui and Guree (1994) under the assumption that there is no electron emission and that the ions and the electrons have Maxwellian velocity distributions. The results are listed in table 2.1.

Table 2.1. The factor $K_f$ for some parameter values.

<table>
<thead>
<tr>
<th>$m_i$ (amu)</th>
<th>$T/T_e$</th>
<th>$K_f (s \mu m^3 \text{eV}^{-1/2})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.05</td>
<td>$7.66 \times 10^2$</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>$1.51 \times 10^3$</td>
</tr>
<tr>
<td>40</td>
<td>0.05</td>
<td>$2.05 \times 10^3$</td>
</tr>
<tr>
<td>40</td>
<td>1</td>
<td>$3.29 \times 10^3$</td>
</tr>
</tbody>
</table>

The electron temperature may be obtained from the characteristics of the probe, whereas the determination of the ion temperature is more difficult. In fact, the ion temperature cannot be determined from measurements made by a Langmuir probe. This is because the ion saturation current is proportional to the Bohm velocity $u_{Bohm}$, the velocity needed to satisfy the condition [Bittencourt 1995]

$$kT_e < m_i u^2$$

(2.9)

for formation of a plasma sheath. Here $m_i$ is the ion mass, $u_i$ the velocity of the ion and $kT_e$ the thermal energy of the electrons. A plasma sheath is the boundary layer between a material body and the surrounding plasma. If a thermal velocity equal to the Bohm velocity is assumed, this velocity will give a maximum ion temperature. As seen in table 2.1, however, the ratio $T/T_e$ does not affect $K_f$ all that much.

2.2 Double layer

In current carrying plasmas, electrostatic structures such as double layers are often observed. As the current in a discharge is increased, the anode sheath moves into the discharge and forms the double layer. Double layers may be observed in laboratory environments, but are also important in space physics and astrophysics [Raadu 1989].

The electric field in the double layer is large within a thin region – the layer – and almost zero outside. Two layers with negative and positive charge density respectively form the layer, giving rise to a substantial deviation from quasi-neutrality. The total net space charge, though, integrated over the double layer volume is close to zero.

The thickness of a double layer is small compared to the characteristic lengths in the surrounding plasma. Due to Bloch (1972) the double layer may be described as follows. Assume that the double layer is confined between two planes at $z=0$ and $z=z_1$. Further, assume only low temperature plasma outside the double layer. If a current flows across the double layer, there is a
source of ions at $z=0$ and a source of electrons at $z=z_1$. With a sufficiently high potential over the double layer, thermal velocity electrons and ions reflected at $z<0$ and $z>z_1$ respectively will not pass through the double layer. Energy and flux conservation give the following equations

\begin{align}
  n_i u_i &= n_0 u_0 = \Phi_i \quad (2.11a) \\
  n_e u_e &= n_1 u_1 = \Phi_e \quad (2.11b) \\
  m_i u_i^2/2 &= e(\Phi_{DL} - \Phi) \quad (2.11c) \\
  m_e u_e^2/2 &= e\Phi \quad (2.11d)
\end{align}

$m_{i,e}$ and $u_{i,e}$ are ion and electron masses and velocities respectively, $\Phi_{DL}$ is the potential at $z=0$ and $\Phi=0$ at $z=z_1$. Integrating the Poisson equation once and applying the condition for the electric field $E=0$ at $z=z_1$ yields

\begin{equation}
  E^2 = C^2 \left[ \phi \frac{\partial \phi}{\partial z} + \mu \phi \left( (\phi_0 - \phi) \frac{1}{\sqrt{2}} - \phi_0 \frac{1}{\sqrt{2}} \right) \right]. \tag{2.12}
\end{equation}

where $C^2 = (2/e_0)(2em_e)^{1/2}$ and $\mu = (m_i/m_e)^{1/2}$. A numerical integration of (2.12) then yields the potential $\phi$ as a function of $z$ [Block (1972)]. Figure 2.2.1 is a qualitative illustration of the result. A corresponding sketch of the electric field is shown in figure 2.2.2.

The current $I$ through the double layer is carried by the free particles accelerated by the potential over the double layer, $\Phi_{DL}$. Since the double layer dissipates energy $I\Phi_{DL}$, the double layer potential will have to be sustained from an external source, in a laboratory set-up an electrical power supply. The accelerated particles will form energetic beams.

Figure 2.2.1. Schematic diagram of the potential of a double layer.
2.3 Negative differential resistance

Negative differential resistance has been observed in double layers [Carpenter and Torvén 1987]. A plot of current as a function of voltage for a double layer would look like figure 2.3.1. The characteristic negative differential resistance is where the sign of $dI/dU$ is negative. This phenomenon may cause large potential amplitude oscillation across the double layer. It has further been related to current disruptions.

The experiments made by Carpenter and Torvén (1987) may be taken as a starting point for a discussion of negative differential resistance. Their experiments concerned a plasma column maintained by plasma sources at each end of a central chamber. The plasma flows from the sources through two apertures, denoted $A_1$ and $A_2$.

Carpenter and Torvén measured the potential structure, results displayed in figure 2.3.2. On the right hand side the potential structure of a double layer is recognised. Between the left aperture and the double layer a potential minimum $V_m$ is seen. $V_p$ and $V_o$ are the potential at the right and left-hand side apertures respectively. They also measured a current-voltage characteristic similar to the one sketched in figure 2.3.1.

Consider the case of a high-potential double layer. Almost all electrons from the right-hand source and almost all ions from the left-hand source are reflected by the double layer. Some of the electrons from the left-hand source are reflected at the potential minimum.

If the potential across the double layer is increased, the ions from the right hand source gain velocity. Consequently the continuity equation for ions, $\nabla \cdot (n_i v_i) = 0$, requires that the ion density decrease, but then, in order to retain plasma quasi-neutrality, the electron density must also decrease. This requires a higher rate of electrons from the left-hand source to be reflected, calling for a reduction of the potential in front of the double layer. The potential minimum $V_m$ thus becomes more negative. Since electrons from the left-hand source dominate the charge contribution to the current across the double layer, the total current decreases giving rise to a negative differential resistance.

The experiment situation in this work is not identical to the one described previously, but the same reasoning may be applied. By analogy, the background plasma may be thought of as the source of electrons and the spherical plasma as the source of ions. A double layer develops between the background plasma and the spherical plasma. If the potential across the double layer increases, then for the same reason as in the experiment by Carpenter and Torvén, a potential minimum develops, reflecting electrons and causing a negative differential resistance.
Figure 2.3.1. Sketched current-voltage characteristic of a double layer.

Figure 2.3.2. Axial potential structure between two sources showing the double layer structure and the potential minimum in the low-potential region. $A_1$ is at the origin. From Carpenter and Torvén (1987).
3 Experimental setup and equipment

A description of the equipment used in the experiments will be given in this chapter. Different probes and methods to measure the plasma potential will also be discussed.

3.1 The Green Tank

The experiments were conducted in a plasma tank, the so-called Green Tank (see figure 3.1.1). The tank is shaped like a horizontal cylinder with curved ends. It has approximately a radius of 1 meter and a length of 1 meter. A working vacuum level of about $10^{-6}$ mbar is attainable. Argon gas may enter the tank as a backing to set the pressure at a desired level.

A background plasma was created by means of a discharge between the main anode and some tungsten filaments. A second anode is used to create another discharge. The anode region of this discharge may take a spherical form, by some authors denoted as a fireball.

Parameters available to the experiment are voltages and currents to the main and second anode, the current to the filaments and the pressure in the tank. The ranges for these parameters are given in table 3.1. Initially the tank is evacuated to a vacuum of approximately $10^{-6}$ mbar. After injection of argon gas the pressure is typically increased by two orders of magnitude above the minimum provided by the pumps, the exact pressure determined by the specific experiment.

First, the background plasma is established with the voltage supply for the main anode when the desired pressure is attained. The plasma may be observed as a purple shimmer in the plasma tank.

The second anode creates the spherical plasma and determines its nature, the voltage and the pressure being the parameters that most strongly influence the mode and the stability of the fireball. Two different modes of the fireball are described in section 5.1. A so-called "diffuse" fireball is generally found at lower pressure than a "sharp" fireball. Thresholds where the two modes appeared to be stable were determined by visual inspection during the experiments.

The well-defined boundaries of the "sharp" mode were readily identified against the background plasma. Also a higher intensity of the light emitted is noted for this case.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U_{\text{main}}$</td>
<td>50-80 V</td>
</tr>
<tr>
<td>$I_{\text{main}}$</td>
<td>2-5 A</td>
</tr>
<tr>
<td>$U_{\text{second}}$</td>
<td>120-300 V</td>
</tr>
<tr>
<td>$I_{\text{second}}$</td>
<td>0.5-2 A</td>
</tr>
<tr>
<td>$I_{\text{filaments}}$</td>
<td>130 A</td>
</tr>
<tr>
<td>pressure, $p$</td>
<td>$6-10 \times 10^{-4}$ mbar</td>
</tr>
</tbody>
</table>

The second anode is designed in such a way that dust may be introduced into the fireball. As described previously an electric double layer (c.f. 2.2) develops between the background plasma and the spherical plasma in the fireball, the plasma consisting of argon ions and electrons.

Argon gas is injected into the tank through a valve, and the pressure maintained constant as a balance between the inlet valve and the working pumps. The voltages at the two anodes were determined by two separate supplies connected in series with a set of resistors, c.f. figure 3.1.2.
The 100-ohm resistor was added to the circuit in the later experiments in order to increase the range of the sharp mode fireball. A device called *dust sprinkler* on top of the tank is used to let the dust into the plasma chamber. The dust particles consist of small grains of aluminium oxide, Al₂O₃ of diameter 5 μm.

Dust of grain size 1 μm were also available but were less frequently used. The dust was contained outside the tank, and dust grains had to fall down through the pipe before actual use of the sprinkler. Thereafter, dust fell into the tank directly from the end of the pipe. The dust sprinkler has three positions of vibration speed "low", "medium" and "high". Evidently more dust fall into the tank with a higher speed of the sprinkler.

There were three grids for the dust to pass, number one and two having transparencies of 70% and the last 48%. The grids force the dust particles to enter in a random fashion. Measurements on the dust sprinkler were made to find the particle flow. Without any plasma present, but under vacuum, the dust sprinkler was turned on at maximum speed for $t$ seconds.

The dust was collected and the location and mass $m_d$ of the dust noted. Given the density of Al₂O₃ 3900 kg/m³, and the size $a$ of a grain, the mass of a single dust grain, $m_p$ is calculated.

The flux of the dust may then be determined as

$$\Phi_{dust} = \frac{m_d t m_p}{t}.$$  \hspace{1cm} (3.1)

Numerically this gives, with $m_d = 0.9$ mg and $t = 90$ s for 5 μm grains, a dust flux of approximately $4 \times 10^3$ s⁻¹. For 1 μm grains the dust flux was found to be approximately $5 \times 10^3$ s⁻¹.
3.2 Method of measurement

Measurements were made with Langmuir probes, described in the following section. The probes could be positioned in three directions $x$, $y$ and $z$, where $y$ is the vertical direction and $z$ along the axis of the cylinder, cf. figure 3.1.1. Coordinate $x$ denotes the rotation around the $z$-axis.

The potential profile of the spherical plasma was determined in an $x$-position sweep with the probe. Successive sweeps with different $z$-positions then enable a 2-dimensional resolution of the potential profile. Two Langmuir probes were used simultaneously to determine the plasma potential difference between the outside and inside of the fireball.

In addition, high frequency probes were used, that could be positioned in the same manner as the Langmuir probes. A current probe was used to measure electrical current to the second anode. Light intensity, which might give information about the diffuse mode of the spherical plasma, was also measured.

LabView, a programme for graphical programming of instrumentation, was used to position the probes as well as for data collection. For the positional sweeps with probes, measuring plasma potential, the data was collected directly by LabView via an internal A/D card.

For other measurements, such as oscillations in the plasma potential, the current to the anode and the light intensity of the plasma, a digital oscilloscope Tektronix TDS 648A was used. The
collected data was then transferred to the computer via a GPIB-bus. The oscilloscope worked well for low frequency potential measurements, but with the high frequency probe used to look for a double layer, the need for short read out time, made it impossible to use the oscilloscope. Instead the high frequency signal was connected via a diode, and the DC-level registered by the internal A/D-card. The oscilloscope could only be used with the probe at rest for high frequencies measurements. For the floating potential of a continuously moving probe, an isolation amplifier has been used and it has been calibrated. An internal A/D card reads the output of the isolation amplifier. This makes the measurements quick.

Collected data was saved in ASCII-format. LabView was run on a dedicated Macintosh computer. For data processing and graphical presentation, Matlab was used.

3.3 Probes

3.3.1 Langmuir probe

Langmuir probes may be used to measure a number of plasma parameters, e.g. the plasma potential. The classical Langmuir probe is a cold, non-emitting, probe but there are also hot, emitting probes. In the experiments conducted for this work, probes capable of both non-emitting and emitting modes were used.

The basic idea for a non-emitting Langmuir probe is rather simple. The bias voltage of the probe is varied and the current to the probe measured. The probe current depends on the probe bias voltage and the plasma parameters. From the characteristic plots of current vs. voltage, various plasma parameters may be deduced, such as the plasma potential, the electron saturation current and electron temperature.

Three regions may be identified in the characteristic plots. Firstly, for high negative probe voltage, the ion saturation region. Then, for slightly less negative probe voltage, there is the exponential region, and finally, with positive voltage relative to the plasma potential, the electron saturation region.

In the ion saturation region, a negative plasma sheath forms around the probe as a shield against approaching electrons. Very few electrons reach the probe, and the current is almost only consists of ions. In the second region, high-energy electrons may reach the probe, changing the shape of the curve in the current-voltage plot. In the electron saturation region, a positive plasma sheath hinders the ions from reaching the probe, similar to what takes place in the ion saturation region. The current is made up of electrons accelerated towards the probe.

For an emitting probe, however, the electrons leave the probe if it is at a negative potential relative to the surrounding plasma, i.e., below the plasma potential. This will cause a distinct difference in the probe characteristics for non-emitting and emitting probes at negative potential (figure 3.3.1). The plasma potential may then be found where the two characteristics differ.

The main advantage of the emitting probe is that the plasma potential may be easily found. The non-emitting probe characteristic shows hardly any sign of saturation at plasma potential if the probe is cylindrical or spherical. Also, it is less sensitive to surface contamination [Boufendi et al 1999]. The floating potential is the potential at which no net current reaches the probe from the plasma. It is the potential a probe would obtain if it were left isolated in the plasma.

The Langmuir probes used in these experiments are very simple, consisting only of a bare wire. If the floating potential is the only parameter to be measured, then the probe is put in emitting mode and the potential of the probe directly determined.

Figure 3.3.2 shows the measured Langmuir characteristic for both emitting and non-emitting probes. The measurements were conducted in the background plasma without the spherical
plasma present. The difference between the two modes may be seen for potentials lower than the plasma potential.

The electron temperature may be determined from the Langmuir characteristic. The current should be proportional to \( \exp(eU/kT_e) \), where \( U \) is the difference between applied voltage and plasma potential in the exponential region. If the logarithm of the current is plotted against the applied voltage, the expected straight line will have slope \( 1/kT_e \), from which the electron temperature is readily calculated.

![Diagram of Langmuir characteristic](image)

Figure 3.3.1. Idealised characteristics for emitting and non-emitting probe.

![Graph of Langmuir characteristic](image)

Figure 3.3.2. Measured Langmuir characteristic with both emitting and non-emitting probe.
3.3.2 The high-frequency probe

The high frequency potentials at an electrostatic double layer require a specific high frequency probe, which may consist of two thin wires, as in figure 3.3.2. The sensitive part of the probe is where the wires are parallel at the top of the figure.

The wires are spirally wound in the middle section of the probe. This design is chosen in order to cancel contributions from each half turn of the two wires. In the bottom section (cf. Figure 3.3.3) a ceramic tube protects the coaxial cables from the plasma.

The desired potential differences are between each probe wire and shielding conductors. The potential difference between the probe wires may be determined after subtraction in a Hybrid-T.

![Figure 3.3.3. Sketch of the high-frequency probe.](image)

3.4 Determination of the plasma potential

Several methods to determine the plasma potential exist, each having its particular advantages and disadvantages. The plasma potential may be determined from the Langmuir probe characteristic as described previously.

Another method is to take the floating potential of an emitting probe as the plasma potential. The floating potential, cf. above, is the potential corresponding to zero net current to the probe. This is experimentally the easiest way to determine the plasma potential.

Still another way is to locate a discontinuity in the characteristic curve, resulting from the change from electron retardation to electron acceleration [Swift and Schwar 1970].

With probes able to work both in emitting and non-emitting mode, the plasma potential may be found by a combination of the hot and cold characteristics. The voltage where the characteristics of emitting and non-emitting probes differ may be used as the plasma potential. This potential is not much different from the floating potential of the emitting probe.
4 Calculations

The charge of an isolated grain and the charging time will be calculated in this chapter. Havnes’s parameter will also be calculated.

4.1 The charge on a single grain

The charge, $Q_d$, a single grain will obtain if surrounded by a plasma is given by equations (2.3) and (2.4)

$$Q_d = 4 \pi \varepsilon_0 a (1 + k \alpha) \phi_s.$$  \hspace{1cm} (4.1)

$k^2 = l/\lambda_D^2$ and $\lambda_D$ is the Debye length,

$$\lambda_D = \left(\frac{\varepsilon_0 k T_e}{4 \pi n_e e^2}\right)^{1/2}.$$  \hspace{1cm} (4.2)

As previously mentioned, the grains used in the experiments had a size of $5 \mu$m. The variables which need to be found are electron density, $n_e$, electron temperature, $T_e$, and the surface potential of the grain, $\phi_s$.

![Figure 4.1.1. Current measured to the probe in emitting mode, when the applied voltage is swept from 50 to 120V. The parameters were $U_{main}=55V$, $I_{main}=2.90A$, $U_{second}=125V$, $I_{second}=0.69A$ and $p=8 \times 10^{-7}$mbar.](image)

The probe is situated in the middle of the fireball during these measurements.
The electron temperature may be found from the voltage-current characteristics of Langmuir probes, and was calculated, as described in section 3.3.1, from the measured current displayed in figure 4.1.1. The average electron temperature was found to be 5.5 eV.

The electron density may be calculated from the electron saturation current. Electron saturation current to the cold probe is reached when the applied voltage equals the plasma potential. The electron saturation current was measured and used to determine the electron density. Equation (2.1a) also applies to the probe used. When the applied potential equals the plasma potential, the equation takes the form

\[ I_e^{sat} = n_e e A \left( \frac{kT_e}{2 \pi m_e} \right)^{1/2}, \]  

(4.3)

or, solving for the electron density

\[ n_e = \frac{I_e^{sat} e A}{e A \left( \frac{2 \pi m_e}{kT_e} \right)^{1/2}}. \]  

(4.4)

Here A is the effective probe area exposed to the electrons. The electron density may be calculated when the saturation current has been determined.

The electron saturation current was found to be 0.42 mA on average. The effective area of the probe was approximately 6 \(10^{-6}\) m\(^2\). Thus the electron density may be calculated, since all factors in (4.4) are either known constants or experimentally measured variables. The electron density for the prevailing conditions was \(1.1 \times 10^{13}\) m\(^{-3}\).

The surface potential of a dust grain, may be estimated using the floating potential of a cold, non-emitting probe. Approximately the same currents will reach the cold probe and the grain, whereas the size and the shape will evidently not be the same for a grain and the probe. The floating potential is approximately 69 V in the centre of the spherical plasma, as seen in figure 4.1.2.

Inserting the calculated values of the parameters in (4.1) and (4.2), the charge collected on a 5 \(\mu\)m grain enclosed in a plasma is found to be \(7.3 \times 10^3\) e. A 1 \(\mu\)m grain would collect a charge of \(2.4 \times 10^4\) e. This is in agreement with approximations by Gorse 1994.
4.2 Charging time

The charging time is given by equation (2.8), requiring the electron temperature and density calculated in the previous section. The atomic mass of argon is about 40 amu, so $K_T$ may be taken roughly as $3 \times 10^5 \text{ s cm}^{-3} \text{ eV}^{-1/2}$ from table 2.1. An estimated value for the charging time for a 5 \( \mu \)m grain is thus 1.2 \( \mu \)s, and for a 1 \( \mu \)m grain 6.4 \( \mu \)s. For this to be valid, the charging time must be much less than the time for the grain to traverse the fireball, being of the order of 100 ms.

4.3 Havnes's parameter $P$

Havnes's parameter $P$, introduced in (2.5), indicates whether the presence of a collection of dust grains influence the charge on any individual grain. In order to use equation (2.5), the density of dust particles has to be known. As described in section 3.1, the density may be determined from the test of the dust sprinkler, where the dust flux $\Phi_d$ was found. From the velocity of the dust particles, $\nu_d$ and the cross-sectional area of the grain flux at the collection plate, $A_d$, the dust density is

$$n_d = \frac{\Phi_d}{\nu_d A_d}. \quad (4.5)$$

The velocity of the dust after falling 0.2 m is 2 m/s and a vast majority of the dust grains end up within a circular area with a diameter of 3 cm. In section 3.1 the dust flux of the 5 \( \mu \)m grains was found to be 4.10$^4$ s$^{-1}$, hence the dust density is 2.9.10$^4$ m$^{-3}$. Equation (2.5) then gives $P = 4.8 \times 10^{-1} << 1$, so the conclusion is that the grain charge of 5 \( \mu \)m grains will not be altered by any collective effect of the dust particles. The 1 \( \mu \)m grains had a flux of 5.10$^5$ s$^{-1}$, giving a dust density of 5.10$^{10}$ m$^{-3}$. Havnes's parameter was found to be $P = 0.17 << 1$. The collective effects of the 1 \( \mu \)m grains might decrease the grain charge.
5 Diagnostics of the spherical plasma

The first part of the experimental work concerned the diagnostics for the fireball. As discussed previously, two modifications of the fireball were found and investigated separately. The potential profile and some plasma parameters (electron temperature, density, thermal velocity, Debye length and plasma frequency) and finally current oscillations and light intensity were experimentally determined.

To distinguish between the sharp and diffuse mode, measurements of the oscillations and their frequencies were made. Since a double layer was believed to exist between the background plasma and the spherical plasma, the spatial profile of the high frequency level was also determined. Also, for the same reason, current disruptions and negative differential resistance were investigated.

5.1 The two modes of the spherical plasma

It became clear early in the experimental work that the spherical plasma could be made to appear in two visually distinct modes: The diffuse fireball and the sharp, from which the first was more easily obtained.

By visual inspection, the difference between the two modes is found at the edges of the fireball and in the intensity light. The sharp fireball, as its name indicates, appears with a distinctive contour against the background plasma, whereas the diffuse fireball falls off gradually. The diffuse fireball also has a lower light intensity than the sharp fireball. Generally, the diffuse fireball exists at a lower pressure than the sharp mode.

The diffuse mode shows temporal and spatial oscillations, and contains a low frequency component, that might be the reason for the diffuse visual appearance of the fireball. Both modes may contain high frequency components. The oscillations and their frequency components were investigated and are described in later sections.

Another direct observation made was that the current to the second anode is higher for the sharp mode fireball. It is the potential of the second anode that is controlled, not the current to the anode. The fireball, regardless of the mode, was only "stable" within some ranges in the external parameters. Stable is here taken as the situation when the shape and size of the fireball is not visually detectable. Because of the intensive light and distinct contours of the sharp fireball, stability is easier to determine for this mode. In the following sections the diagnostics of the spherical plasma are described and the two modes of the fireball compared.

5.2 Plasma potential

The plasma potential was investigated using Langmuir probes, as described in sections 3.3 and 3.4. A plasma potential profile of the spherical plasma was obtained through translation of the probe along the z-direction, and rotation of the probe around the z-axis, yielding the dependence in the x-coordinate. See figure 3.1.1. Different methods to determine the plasma potential are described in section 3.4. In these preliminary measurements of the plasma potential profile, the voltage where the characteristics of emitting and non-emitting probes differ was used as the plasma potential, whereas the floating potential was used in later measurements.

Figures 5.2.1-2 show the plasma potential structure of the fireball in diffuse and sharp mode. It may be seen that the potential is higher in the spherical plasma than in the background plasma. In figure 5.2.1 a higher plasma potential is seen for high z values than for low values of z, z is directed towards the main anode. This indicates a potential gradient along the central axis of the
tank. In the sharp mode potential structure, figure 5.2.2, though, this is not as clearly seen. The unsmooth features in the sharp mode potential structure appears because the fireball became unstable during the measurement, resulting in lower and quickly changing potentials. Positional changes of the probe are believed to be the cause of disturbances on the fireball.

Figures 5.2.3-4 and 5.2.5-6 show the plasma potential in the diffuse and sharp modes, as function of x and z respectively. From these plots it is clear that the potential is symmetric in x. The higher potential for increasing z-coordinate makes the profile unsymmetrical in this direction. Since the fireball is symmetric, the potential profile should also be symmetric with a maximum in the middle of the spherical plasma. Most of the potential drop at the edge of the fireball occurs over a small spatial distance (figures 5.2.4 and 5.2.6). The potential drop is approximately 15-20 V on the low z side. On the other side, closer to the main anode, the potential drop is about 10 V for both diffuse and sharp mode.

The angular position (x-coordinate) shows a potential drop of almost 15 V on both sides and in both modes. In summary the potential structure is symmetric with a maximum in the middle of the fireball with a potential drop of 15-20 V over a small distance at the edges of the spherical plasma. The symmetry is somewhat disturbed on the side facing the main anode.

Figure 5.2.1. Plasma potential structure in the diffuse spherical plasma.
Figure 5.2.2. Plasma potential structure in the sharp spherical plasma.

Figure 5.2.3. The plasma potential as function of $x$ in the diffuse mode.
Figure 5.2.4. The plasma potential as function of $z$ in the diffuse mode

Figure 5.2.5. The plasma potential as function of $x$ in the sharp mode
Figure 5.2.6. The plasma potential as function of $z$ in the sharp mode

5.3 Plasma parameters

In section 4.1 was described how the electron temperature and the electron density were obtained. Inside the spherical plasma, the they were found to be $5.5 \, \text{eV}$ and $1.1 \times 10^{15} \, \text{m}^{-3}$, respectively. The results were similar in both modes. The electron Debye length corresponding to these values is 0.15 mm.

The electron thermal velocity at 5.5 eV is $1.4 \times 10^6 \, \text{m/s}$, and the corresponding electron plasma frequency $1.9 \times 10^9 \, \text{rad/s}$. Both the electron density and the electron temperature are lower in the background plasma than in the fireball. The electron temperature and the electron density were found to be $4.0 \, \text{eV}$ and $4.2 \times 10^{14} \, \text{m}^{-3}$ respectively in the background plasma. This gives a Debye length of 0.20 mm, a thermal electron velocity of $1.2 \times 10^6 \, \text{m/s}$ and an electron plasma frequency of $1.2 \times 10^9 \, \text{rad/s}$.

5.4 Oscillations

With the spherical plasma in the diffuse mode, the light intensity did appear not to be constant. This is in contrast to the case for the sharp mode, where the light intensity was constant. Since differences between the two modes were to be investigated, the light intensity was measured in the diffuse mode. The light was registered by a photomultiplier.

The output voltage, proportional to the intensity of the incoming light, was displayed on an oscilloscope and the data collected by the computer. The cause of the "diffuseness" was now of interest, and two mechanisms were considered: Either the fireball is oscillating spatially, or it is extinguished for short periods. If the spherical plasma would be oscillating in time, the successive fireballs would probably not have exactly the same spatial position. Therefore small spatial variations are likely even if the main cause of the diffuse mode is temporal oscillations.
Observing the measured light intensity it was found that the intensity varied in time and that the variation was periodic, see figure 5.4.1. The increase in light intensity had a frequency of approximately 5.5 kHz and the amplitude three times larger than the ground level noise amplitude. Thus it was concluded that the fireball mode is seen as diffuse because of the temporal oscillations of the light intensity.

When the light intensity of the sharp mode was measured, no temporal deviation from the ground level of intensity was noticed. To support the explanation of the diffuse mode, correlations between these oscillations in light intensity and other measurable parameters were considered for investigation. The current to the second anode, which creates the discharge with the spherical anode region, was measured, as well as the floating potentials of two emitting Langmuir probes. Of interest was the potential difference between the inside and the outside of the plasma. One of the probes was situated inside the fireball, whilst the other one gave the plasma potential in the background plasma.

The question to be answered was if changes in plasma potential could be correlated with the changes in light intensity. Temporal changes in the spherical plasma should be detectable in the current to the second anode and in the potential difference. If the fireball would be extinguished, the difference in plasma potential would be markedly less than if the fireball would not be present.

The current was first measured using a current probe. This probe was placed between the anode and the two seven ohm resistors, see figure 3.1.1. The 100-ohm resistor was not in the circuit in this experiment. Results of the measurements are shown in figure 5.4.2. The potential difference is low, i.e. the potential of the background plasma is approximately the same as the potential measured in the middle of the spherical plasma when the light intensity is at low.

The measured difference is approximately 8 V and is due to the potential gradient discussed in section 5.2. Hence, the spherical plasma is considerably weakened. There is a current increase at the same time as the light intensity rises. The current probe, which is a current transformer, cannot detect a DC-component of the current. The current displayed in figure 5.4.2 and the peaks in the plasma potential difference, and the well-correlated light intensity maxima, shows that the fireball remains turned on for a shorter time than it is turned off.
Figure 5.4.2 Current, light intensity of and potential difference between the inside and outside of the diffuse fireball vs time.

To determine whether the fireball is completely extinguished or not, an additional measurement of the current is needed. If the current goes down to zero in an absolute measurement, this will prove that the fireball is extinguished.

The potential on each side of one of the seven-ohm resistors was measured and the current calculated from the measured voltage and the known resistance. The result of the measurement is displayed in figure 5.4.3, where the current probe measurement is also shown. Within the experimental precision, the measured current is zero during the periods corresponding to low light intensity and small difference in plasma potential.

The current peaks have the same frequency, 5.5 kHz, as the light intensity peaks. Oscillations in current, light intensity and plasma potential in the fireball are correlated. The conclusion is that the fireball is turned off – extinguished – for a period of time and then turned on again for a shorter period of time.

The diffuse mode is periodic in appearance, low frequency oscillations were not detected in the sharp mode and therefore the fireball is assumed to be stable. The current changes seen in figure 5.4.3 are known as current disruptions. They are associated with electrostatic double layers [Axtens et al 1996].
5.5 The Double Layer

A double layer, likely to exist at the edges of the fireball, is characterized by a large change in potential over a small spatial distance. In the double layer, electrons will be accelerated towards the higher potential side in an electron beam, giving rise to beam plasma instability with high frequency oscillations. If the density of the plasma is low compared to the density of the background plasma, oscillations close to the electron plasma frequency may occur.

The measurements were conducted using the dedicated high-frequency probe described in section 3.3.2. The probe was moved through the fireball along the axis. In this experiment, the sharp mode spherical plasma that the sharp mode is constantly changing.

When measuring the field, instead of taking the field, it is important, and the field shows two measurements are seen. It is typical over a short distance indicating that a double layer exists. The absolute value of the axial parameter is necessary. Figure 5.5.1 shows that the plots, two peaks increase sharply. For the spherical plasma, a low value obtained interaction between...
Figure 5.5.1. Two high-frequency potential profiles of a spherical plasma in the sharp mode.

Although the diffuse mode could not be used to determine the characteristic high frequency potential profile of a double layer, it is still worthwhile to measure the high frequency profile. The obtained profile is shown in figure 5.5.2, where three peaks are seen. The velocity of the probe is lower in this measurement than in the sharp mode measurement in figure 5.5.1. There are high frequency oscillations also in the diffuse mode.

Figure 5.5.2. High frequency profile of the diffuse mode for two different probe velocities.
5.6 Negative differential resistance

Negative differential resistance is a phenomenon associated with double layers [Carpenter and Torvén 1987]. An explanation was given in section 2.3. Since a double layer was found in this experimental set-up, it was natural also to look for negative differential resistance.

The voltage at the second anode (cf. figure 3.1.2), $U_{\text{second}}$, was now varied. The voltage over the 100-ohm resistor, $U_R$, was measured using a HP 3478A multimeter. This gave the current through the resistor, $I_R$, and also the voltage between the second anode and ground, $U_{\text{anode-grounds}}$, as the difference between $U_{\text{second}}$ and $U_R$. The result can be seen in figure 5.6.1, showing a non-linear current-voltage characteristic.

The result may be compared with the theoretical characteristics in figure 2.3.1. The measured voltage and current are similar to the first part of the theoretical curve. For negative differential resistance, the significant part is the slope on the right hand side of the maximum. The slope of the measured curve is decreasing, but the corresponding maximum in the theoretical curve is not seen in the experimental curve.

Since the existence of a double layer is supported by other measurements on the spherical plasma, the negative differential resistance would probably be seen if the voltage could be increased. This was, however, not possible in the current experimental set-up, since a higher current through to the discharge might damage both the resistor and the anode.

![Figure 5.6.1. The current-voltage characteristic of the spherical plasma for measured values * and the line fit.](image)

5.7 High and low-frequency components in potential oscillations

The contents of frequency components of the two modes were compared. The dependence on spatial position in the spherical plasma was also considered. The high-frequency potential was measured using the high frequency probe, and the floating potential of an emitting Langmuir probe was used for low frequency potentials. The probes were stationary and not moved during the measurement. The frequency spectrum was determined with FFT (Fast Fourier Transform) function of the oscilloscope.

The results of the measured low-frequency spectrum in the diffuse mode are displayed in figure 5.7.1. The measurement was made with the probe in the middle of the fireball. In the upper panel
of figure 5.7.1 the ground frequency is seen to be 4.6 kHz. The second peak in the upper panel is at the double ground frequency. The peaks in the upper and the middle panel are separated by 4.6 kHz and thus higher harmonics of the main frequency.

The amplitude of the peaks is generally lower at higher frequencies, the decay at even higher frequencies shown in the lower panel. The position of the probe did not affect the frequency spectrum. Hence, the frequency of 4.6 kHz is the main frequency responsible for the low frequency oscillations in the diffuse fireball.

The time dependence of the plasma potential oscillation is displayed in figure 5.7.2. The peaks appear at intervals 4.6 kHz. In the sharp mode the measured low frequencies gave the result presented in figure 5.7.3. As is seen, no distinctive low frequency component is present for this mode.

Figure 5.7.1. The low frequency spectrum of the diffuse mode spherical plasma.
Figure 5.7.2. Time dependent plasma potential oscillations corresponding to the low frequency spectrum of figure 5.7.1.

Figure 5.7.3. The low frequency spectrum of the sharp mode spherical plasma.

The absence of low frequency components in the sharp mode would be expected from the previously discussed properties of the sharp mode. Other measurements show oscillations at low frequencies in the diffuse mode, see section 5.4. The frequency observed was approximately 5.5 kHz. It was estimated from the period of the peaks in light intensity and potential difference, and
from the current disruptions. The difference between the two measured frequencies is small. The two measurements agree.

From the high frequency profile of the sharp mode established in section 5.5, it is clear that high frequencies are present at the boundary between the background plasma and the spherical plasma. Measurements in the middle of the sharp fireball could not resolve any high frequency components. The frequency spectrum at the boundary of the sharp mode fireball is seen in figure 5.7.4. In the range displayed, up to 250 MHz, two distinctive peaks are seen above the ground level. These peaks reside at 62.5 MHz and 121.9 MHz. The latter is approximately two times the first, assumed as main frequency. At 180 MHz there is an enhancement in the curve, but no distinct peak is observed, neither at 240 MHz.

![Frequency Spectrum](image)

**Figure 5.7.4. The high-frequency spectrum of the sharp mode spherical plasma.**

The high-frequency content was also measured for the diffuse mode. The result of this measurement was a high-frequency component in agreement with the measured frequency in the sharp mode. Figure 5.7.5 shows the high-frequency spectrum measured at the edge of the fireball. One sharp peak at 84 MHz and a less distinctive peak at 172 MHz are seen in this spectrum. The main peak of the sharp mode was at 64 MHz, close to the main peak of the diffuse mode. The decline in the frequency spectrum is displayed in figure 5.7.6.

The two peaks in the diffuse mode are broader than the peaks in figure 5.7.4. The repeated creation and extinction of the fireball in the diffuse mode probably causes the broadening in the diffuse mode. This infers that there exists a non-stationary discharge during part of the time, which may give rise to oscillation at other frequencies. The oscillations as function of time are displayed in figures 5.7.7 and 5.7.8. The first of those figures shows the periodic high-frequency oscillations, while the second one shows bursts in the potential. These bursts are of low frequency and not periodic.

Measurements of the high-frequency spectrum were also carried out in the centre of the diffuse mode spherical plasma. High frequencies were also detected there. They corresponded with
measured high frequencies at the boundary of the spherical plasma in the sharp mode. The main peak was at 64 MHz, with a second peak at 126.6 MHz, cf figure 5.7.9.

The two modes are different at low frequencies, but are similar in high frequencies. There are no low frequency oscillations in the sharp mode and, as noted before, it is the presence of low frequencies in the diffuse mode that cause its visual appearance. The high frequencies are associated with the double layer and are only detected at the edge of the sharp mode spherical plasma.

High frequencies are detected in both in the middle part and the outer part of the diffuse fireball, since the fireball is shifting position in the diffuse mode, not only performing temporal oscillations. The changing conditions in the diffuse mode are primly affecting the high plasma frequencies in the outer parts of the fireball, as seen in the measurements.

![Figure 5.7.5. The high-frequency spectrum of the diffuse mode spherical plasma measured in the outer part of the fireball.](image-url)
Figure 5.7.6. The decrease in the high frequency spectrum for the diffuse mode.

Figure 5.7.7. High-frequency oscillations in the diffuse mode.
5.8 Is levitation of dust possible?

If electromagnetic forces balance the gravitational pull on a grain, the grain would float in the spherical plasma. There is no magnetic field in these experiments, so the force equation for the grain becomes
\[ F = qE + F_g \]  \hspace{1cm} (5.1)

where \( F_g \) is the gravitational force and \( qE \) the electrostatic field. If the direction vertically down from the second anode is called \( s \), and \( Q_d \) and \( m_d \) are charge and mass of a grain, then putting the left hand side of (5.1) equal to zero and using \( E = -\nabla \phi \) gives

\[ \frac{d\phi}{ds} = \frac{\Delta \phi}{\Delta s} = \frac{m_d g}{Q_d}. \]  \hspace{1cm} (5.2)

A value of \( Q_d \) is given in section 4.1 as \( 2.4 \times 10^5 e \) and of \( m_d \) as \( 2.55 \times 10^{-13} \) kg for a 5 \( \mu \)m grain of \( \text{Al}_2\text{O}_3 \). From section 5.1, a potential difference of 15 V is estimated. The size of the spherical plasma in the \( y \) direction does not exceed 0.15 m. With the values given, the left hand side of (5.2) is 100 V/m and the right hand side 65 V/m. Hence, it would be possible for a grain to float in the spherical plasma. The kinetic energy of the grains after a fall of 0.15 m is in the order of 2 MeV. A potential over the edge of the fireball of 10-15 V can stop grains with energy of 2.4-3.6 MeV.

Since these energies are close, the velocity of the grains cannot be neglected. The grains might be captured in the fireball, but it is not likely that they will stay there for a long time, since the potential is low and not constant over time. The ratio \( m_d/Q_d \) is the same for 1 and 5 \( \mu \)m grains. The kinetic energy of a 1 \( \mu \)m grain is 18 keV, well below what the double layer may retain. Hence, it is likely that the 1 \( \mu \)m grains will remain floating in the fireball.

### 5.9 Disturbance on the plasma by the probes?

When one of the Langmuir probes approached the spherical plasma, a disturbance was often noticed. The spherical plasma seemed to try to "avoid" the probe. The fireball changed position. It looked as if the probe pushed away the spherical plasma. When the probe entered a sharp mode fireball, it occasionally made the fireball unstable, and at times the fireball changed mode to the diffuse mode. The effect did not only appear when the probe was collecting data or put in the emitting mode. It seemed as if it was the presence of the probe that disturbed the fireball.
6 Influence of dust on the spherical plasma

The second part of the experimental work was to investigate the influence dust grains might have on the spherical plasma. Both plasma modes were exposed to dust. The dust particles were grains of aluminium oxide, with a diameter of 5 μm. In some measurements grains of 1 μm diameter were used. The dust inlet was described in section 3.1. The experiments conducted in the search for dust effects included investigations of the plasma potential, its high and low frequency components and an investigation of temporal oscillations in the diffuse mode.

6.1 Plasma potential

The initial measurements with dust in the spherical plasma, were potential sweeps, using the floating potential of an emitting Langmuir probe. The probe was rotated around the z-axis. Both modes were examined, with and without dust present. Here, the 5 μm grains were used.

Figures 6.1.1-2 show the measured plasma potential of the sharp mode as function of coordinate x, see also figure 3.1.1. The difference between the two measurements with dust, were the velocity of the dust entering the plasma. The dust sprinkler may be set to three different speeds. The results shown represent measurements with minimum and maximum velocity of the dust. No change in the potential can be seen with dust present. The appearance of the potential curve in the maximum dust velocity case is not as smooth as the corresponding non-dusty potential. The disruptions seen at the edge of the fireball are probably an effect of other disturbances, such as the probe, and not due to the dust. The results of the measurements on the diffuse mode fireball are shown in figure 6.1.3. As is often noticed, the potential is not smooth due to the diffuse effect. No clear influence of the dust on the plasma potential in the diffuse mode can be seen from these measurements.

Figure 6.1.1. Plasma potential without dust (above) and with dust (below).

Maximum dust velocity and sharp mode.
Figure 6.1.2. Plasma potential without dust (above) and with dust (below).
Minimum dust velocity and sharp mode.

Figure 6.1.3. Plasma potential without dust (above) and with dust (below).
Maximum dust velocity and diffuse mode.
6.2 High frequencies and low frequencies

The spatial profile of the high frequencies of the sharp mode spherical plasma was measured with 5 μm dust grains. In figure 6.2.1 the result is compared with a measurement without dust present. The only noticeable difference is a shift of the positions of the high frequency peaks towards higher z in the measurement with dust. This indicates a positional shift of the fireball, but shift is sometimes seen also with no dust present. A small and slow change in position may take place even in the sharp mode. The conclusion is that this shift is not an effect of the dust.

In the search for effects on the plasma caused by the dust, smaller grains of size 1μm were used when the low frequency of the diffuse mode was measured. Also, the 100-ohm resistor, seen in figure 3.1.2, was not present in the circuit. The result is seen in figure 6.2.2 in three frequency ranges. Compare this result with figure 5.7.1, where no dust was present. None of the peaks seen in figure 5.7.1 are seen in the measured spectra with dust present. The effect observed will be further investigated in the next section, where the temporal plasma potential oscillation is investigated.

![Figure 6.2.1. High frequency profile of the sharp mode spherical plasma. Upper figure with dust, lower figure without dust.](image-url)
The high-frequency spectra of the sharp and diffuse modes were measured with no evident influence observed from the dust. Figure 6.2.3 shows two measurements at high-frequency, one with dust present, and one without dust. These measurements were conducted at the edge of the sharp mode spherical plasma. The results with and without dust were similar. The main peak in all three measurements was close to 60 MHz, as was also found in the earlier high frequency measurements.

Three or four peaks are seen in each of these measurements, all separated by approximately 60 MHz. In the diffuse mode, the measurement took place in the centre of the fireball. The results are shown in figure 6.2.4, with the main peak at 100 MHz in all three cases. The second peak, around 200 MHz, is noticeable in the non-dust frequency spectrum but less evident in one of the dust spectrums and flattened in the second. The main peak is somewhat broader in the dusty cases. Whether these two effects are related to the dust or not, cannot be determined with absolute certainty. The diffuse mode is the more unstable and may undergo changes also with no dust present.
6.3 Plasma potential oscillations

So far, little or no effect of the dust has been observed. One effect, though, was seen in the low frequency spectra. Under the same conditions, with 1 μm dust grains and without the 100-ohm resistor, the plasma potential oscillations were investigated. When the oscillations in the diffuse mode were measured and plotted against time, an effect caused by the dust was observed. Figure 6.3.1 shows the complete measurement of the oscillations in potential during 0.25 s. The peaks are farther apart in the dust case. The difference between the two measurements is most clearly seen during the first 0.075 s of the measurement with dust.
A magnification of the first parts is presented in figure 6.3.3. In this figure the number of peaks is much lower when the dust is present. The peaks are also separated by a relatively large period of time. Figure 6.3.2 shows the oscillations at a later time magnified. The difference is not as obvious as in figure 6.3.3, but is still noticeable.

The interpretation of the observation is that the diffuse fireball is put out for longer periods of time when there is dust present compared to the case when there is no dust. This result is correlated with the loss of peaks in figure 6.2.2.

![Figure 6.3.1. Temporal plasma potential (V) oscillations. Upper panel without dust, lower panel with dust.](image1)

![Figure 6.3.2. Magnified part of the end in the figure 6.3.1. Plasma potential in volts. Upper panel without dust, lower panel with dust.](image2)
Figure 6.3.3. Magnified part of the beginning in the previous figure.

Plasma potential in volts. Upper panel without dust, lower panel with dust.

6.4 Visual observation of dust.

During the experiments the dust collected beneath the spherical plasma was observed. The dust grains were collected on a black plate so that the white dust could be observed through a window in the tank. The grains used in the experiments had a size in the order of μm. Single grains cannot be seen.

Larger aggregations of grains were seen falling down on to the collecting plate, which may be explained by electrostatic attraction between dust grains. During the time spent in the spherical plasma, they might grow by collisions into larger aggregates. It cannot be excluded that also small dust particles fall down together with the large particles since they are not visible.
7 Discussion and conclusions

Two modes of the spherical anode plasma were identified, the sharp mode and the diffuse mode. They could be distinguished visually. The sharp mode has more distinctive borders against the background. The light intensity is also higher in the sharp mode. In the diffuse mode, the passage from the fireball to the background plasma is seen as more gradual. It is easy to distinguish between the two modes by a visual inspection. The modes were investigated and the difference between them was found. The fireball was found to oscillate in time in the diffuse mode. From different measurements of light intensity, current to the anode and potential, it was concluded that the diffuse appearance is caused by the fast creation and destruction of the fireball. The sharp mode consists of a steady fireball, without low frequency oscillations.

The measured plasma potential structure indicates a double layer at the boundary between the background plasma and the spherical anode plasma. This is confirmed by high frequency measurements that reveal signatures typical for double layers. The negative differential resistance associated with double layers could not be confirmed in these experiments. Based on other double layer measurements, though, it may be argued that negative differential resistance exists and is responsible for the oscillations in the diffuse mode.

The influence of dust on the spherical anode plasma was also investigated. Two sizes of grains were used, 1 and 5 μm. No or little effect could be seen from the larger grains. The smaller grains affected the diffuse mode in that the fireball was turned off for longer periods of time.

One possible explanation for the observed behaviour could be recombination at the dust grains. The recombination rate must be compared with the ionisation rate. Electrons of two different origins can ionise the argon gas: thermal electrons and accelerated beam electrons. The thermal electrons with a temperature of 5.5 eV gave an ionisation rate of $1.2\times10^{-9}$ s$^{-1}$m$^{-3}$. The electrons accelerated over the double layer gave an ionisation rate of approximately the same order.

The recombination rate is given by $n_i n_e A_g n_g$, where $n_i$ and $n_e$ are ion density and ion velocity, the Bohm velocity gives the ion velocity, $A_g$ is the surface area of the grain and $n_g$ is the dust grain density. Quasi-neutrality requires that the ion density equals the electron density. The dust density for the 1 μm grains was found in section 4.3 to be $5.1\times10^{10}$ m$^{-3}$. The recombination rate was found to be $2.5\times10^{18}$ s$^{-1}$m$^{-3}$, which is small compared to the ionisation rate. The calculations are rather crude, and the recombination may cause some disturbance.

If the grains remain in the fireball, as may be argued from the calculations in section 5.8, then the dust density and the recombination rate must increase, making the recombination more important. This mechanism could be the cause of the enhanced periods of extinction, but the suggestion cannot be established from the measurements in this work. A model for the extinctions in the diffuse mode with dust present require better estimations for some important parameter, e.g. the dust density.
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