Study of the 3D plasma cluster environment by emission spectroscopy

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New Journal of Physics 11 (2009) 113023 (13pp)
Received 19 June 2009
Published 10 November 2009
Online at http://www.njp.org/
doi:10.1088/1367-2630/11/11/113023

Abstract. Three-dimensional (3D) plasma clusters were formed inside a quasi-neutral plasma of very small size (38 mm³) obtained by applying a radio frequency (rf) to a small electrode at the edge of a main plasma. In order to find the density of such a plasma, spectroscopic analysis at three wavelengths was performed. The emission structure of the small plasma as well as of the whole discharge was obtained with a resolution of 0.5 mm. The optical thickness of the plasma allowed us to apply the steady-state corona model for the calculation of the plasma density. The density was estimated to be \( \simeq 2.8 \times 10^{16} \text{ m}^{-3} \) in the small plasma, one order higher than in the main plasma volume.
In the last 20 years there has been a growing interest in the field of complex (dusty) plasmas, which are plasmas containing small particles of solid matter. This interest has mainly arisen in two very different fields in physics: astrophysics and industrial plasma research, particularly microelectronics. Natural dust fills the universe; planetary rings, comet tails and interstellar clouds consist of dust [1]–[3]. In material processing dust is often present due to sputtering processes from plasma reactor walls and electrodes. During the processes of etching or deposition particles of different substances appear in the region of the processed surface and can influence both the parameters of the process as well as the quality of a product [3, 4]. Therefore, the study of the particle behavior is essential in these industrial fields. Under laboratory conditions dust particles are externally introduced in the plasma and their behavior is studied. Different phenomena such as charging of particles, forces acting on them, waves and instabilities, phase transitions and transport phenomena are subjects of investigation.

After the laboratory discovery of plasma crystals [5], which have similar properties to the solid state, enormous interest developed in the field of complex plasmas. In ground-based experiments dust particles usually form crystalline two-dimensional (2D) layers where gravity and electric field balance. In microgravity experiments it is possible to obtain 3D structures, free from the vertical gravitational stress, which have an empty region (void) inside. In addition to these 3D systems there have been attempts to obtain 3D clusters in ground laboratory experiments [6, 7], where the gravity is compensated by electrostatic/thermophoretic forces. The dynamical behavior of these 3D clusters is still a challenge for investigation, since it requires a 3D diagnostic to detect fast processes. The 3D plasma clusters obtained in a ‘secondary plasma’ using an adaptive electrode and 3D diagnostics with simultaneous determination of all coordinates are described in [8]. In order to characterize the behavior in the clusters it is necessary to know the parameters of the plasma at the position where the clusters are situated.

In this paper, we present a study of the cluster environment considered in [6, 8]. Because of the very small size and the radio frequency (rf) nature of this plasma, Langmuir probes cannot be used. Therefore, spectroscopic analysis has been chosen as the most suitable method of plasma diagnostics. The emission spectroscopy method is very much in use for...
Figure 1. An example of the ‘secondary plasma’ view (small very bright glow on the lower electrode in the sheath of the main plasma, which is the large oval-shaped glow above) with rf voltage $V = 60$ V applied to the segment of the adaptive electrode (opposite phase with respect to the upper driven electrode). $P = 88$ Pa, and the driven electrode excitation $V_{\text{RF}} = 250$ V. The horizontal cylinder of light is from a window and should be disregarded.

the study of different plasma discharges. The literature review shows that this method is successfully applied for plasma characterization in low pressure inductively coupled as well as capacitively coupled rf plasma discharges, in particular, to obtain electron temperature and plasma density [9]–[11]. Optical emission spectroscopy diagnostics is widely applied in surface processing and chemically reactive plasmas for the density determination of a reactive component [12] or sputtered atoms [13].

1. Experimental evidence

The experiments were performed in the PKE-Nefedov chamber which has glass walls [14]. The upper electrode is driven at 13.56 MHz; the lower electrode is the segmented ‘adaptive’ electrode, which consists of 57 squared segments, each of 16 mm² area. Applying an additional rf voltage to one segment and keeping the others floating, it is possible to obtain a glow (small ‘plasma ball’ or ‘secondary plasma’) inside the sheath of the main plasma. This ‘secondary plasma’ is situated just above the lower electrode and its brightness depends on the amplitude of the applied rf voltage (an example of the ‘secondary plasma’ glow in the chamber is shown in figure 1). Melamine formaldehyde particles of 3.4 µm diameter were injected into the discharge and levitated in the plasma sheath near the lower electrode. When the small ‘plasma ball’ appears, particles gather in this glow from the plasma sheath. More details about the adaptive electrode are given in [15]. In our experiments the voltage on the driven electrode was 300 $V_{\text{pp}}$; on the small segment and about 150 $V_{\text{pp}}$ in the opposite phase. All clusters were obtained in an argon discharge at pressures of about 60 Pa; spectroscopic measurements were made at this pressure and at 30 Pa for comparison.
Figure 2. Sketch of the apparatus for the spectroscopic measurements in the plasma chamber. PMP is the photomultiplier, $T$ and $r$ are the length and the radius of the additional tube, $L$ is the plasma dimensions and $\varepsilon$ is the thickness of a chamber glass plus plasma sheath.

2. Spectroscopic analysis

The spectroscopic analysis of the ‘plasma ball’ intensity was performed using a photomultiplier with three filters with a bandwidth approximately 10 nm (wave length $\lambda = 350$ nm, which corresponds to a bunch of ionic lines with the upper level of excitation about 23 eV; $\lambda = 550$ nm with three relevant atomic lines of 549.5 nm (15.3 eV), 555.8 nm (15.13 eV), 560.6 nm (15.11 eV); and $\lambda = 810$ nm with two atomic lines of 811.5 nm (13.07 eV), 810.3 nm (13.10 eV)). In measurements involving band-pass filters care should be taken to exclude unwanted contributions from impurities that may be present in the residual gas. In fact the nitrogen lines 355.3 (molecular) and 357.7 (atomic) were considered. Khan et al [16] show a spectrum obtained in Ar and 30% N$_2$ at 50 Pa, at about our pressure. The line at 357.69 is indeed large. However, with a background vacuum of $10^{-5}$ mBar we have a ratio of N to Ar of $2 \times 10^{-5}$. The N$_2$ line should appear in our spectrum 10$^4$ times smaller. The paper [17] reports atomic N lines in a nitrogen/argon mixture. There is a line of small intensity at 355.3, at the edge of our filter, with an argon flow rate of 13 l min$^{-1}$ and N$_2$ flow rate of 70 ml min$^{-1}$. We had a very limited desorption (glass chamber rarely opened and electrodes heated by the plasma itself). We could then conclude that the possibility of the influence of N$_2$ is negligible in our experiments.

The ion distribution in plasma volume can be considered to be homogeneous along the optical axis in the main plasma volume because of symmetry. The small plasma is situated in the sheath of the main plasma where there is no emission, hence the light taken is only from the small plasma spot. We also consider as negligible the spectral line broadening in this particular application. In general broadening and shifts may affect our method only at the edge of the filter because otherwise the integral of the line is conserved. If we scale the broadening reported in [18], we find that going from 10 to $10^4$ Pa the broadening is 0.01 nm.

In the experiments, we used a small tube of 0.4 mm internal diameter and 215 mm length to obtain a space resolution of 0.5 mm in the center of the chamber (see figure 2). For each point we took 100 measurements of intensity with 50 ms integration time, then we averaged them to obtain one intensity value for each distance from the electrode. In this way the error on the intensity is reduced to within the points’ symbol size. By scanning the chamber vertically we obtained the structure of our discharge, with the main plasma glow, two sheath regions and the ‘plasma ball’ glow. The resolution gives us eight points in the ‘secondary plasma’ scanning. In figure 3, the light emission structures at 30 and 60 Pa are shown. In these two figures the large peak from the left shows a very bright glow just above the lower electrode, where the ‘secondary plasma’ is. Almost all our clusters are situated in this region. Above the large peak one can see
Figure 3. The distribution of intensity between electrodes in the discharge measured by photomultiplier at 60 and 30 Pa pressure. The lower electrode is at 0 mm and the upper one is at ~30 mm.

a small peak at 60 Pa but not at 30 Pa. This is the spherical shape part of our small ‘plasma ball’ (figure 1). The third large peak, which is present for 60 Pa as well as for 30 Pa, is the main plasma glow. The intensity of the ‘secondary plasma’ is higher than the intensity of the main plasma in all spectra at 60 Pa but it is lower for most of the curves at 30 Pa. At pressures lower than 30 Pa the small ‘plasma ball’ disappears due to the expansion of the main plasma sheath.

3. Corona model

In order to estimate the density of the ‘secondary plasma’ from the spectroscopic data the corona model has been found suitable. In the corona model it is assumed that the electron density is low enough that collisional de-excitation can be neglected. Then all upward transitions can be considered collisional from the ground state and all downward transitions are radiative. Spontaneous transitions from higher states are considered negligible because higher levels are progressively less populated. These hypotheses are validated ‘a posteriori’ by the fact that
results obtained with different lines and different methods coincide. The model is applicable in several cases for the analysis of low density laboratory plasma, when the plasma is optically thin, i.e. absorption of radiation can be ignored [19]. The experimental determination of the plasma optical depth was obtained using the ‘mirror method’. For this purpose a mirror was placed behind the plasma source to compare a single pass intensity, $I_s$, and the intensity obtained with the mirror, $I_T$. In these terms the optical depth $\tau$ can be written as

$$\tau = \ln \frac{I_s}{I_T - I_s}. \quad (1)$$

If $\tau < 1$ the plasma is optically thin and the absorption is low. The intensity measurements were made in the pressure range from 30 to 90 Pa using a bolometer sensitive to the entire visible spectrum. The optical depth $\tau$ was equal to 0.6; this confirms that our plasma is optically thin and the steady-state corona model is a reasonable approximation.

In this model the contribution of the electron energy distribution function is included in the excitation function as was pointed out in [20]

$$E_m = n_e \int_{E_{tm}}^{\infty} \frac{2\varepsilon}{m_e f(\varepsilon) \sigma_m(\varepsilon)} \, d\varepsilon, \quad (2)$$

where $n_e$ and $m_e$ are the electron density and mass, respectively, $\sigma_m$ is the electron impact excitation cross-section as a function of the electron energy $\varepsilon$, $E_{tm}$ is the threshold excitation energy for the level $m$. Spontaneous emission then depopulates the exited state with transitions to a number of other states. The probability of transition between the quantum levels $m$ and $n$ is given by the Einstein coefficient $A_{mn}$. Therefore, the measured intensity of the atomic lines will be proportional to

$$I_{mn} = G_a n_a E_m A_{mn} \sum_l A_{ml}, \quad (3)$$

where $n_a$ is the density of atoms in the ground state and $\sum_l A_{ml}$ takes into account the relevant transitions between level $m$ and other levels $l$. $G_a$ is the geometric constant factor. For the ionic lines a similar formula can be written

$$I_{hj} = G_i n_i E_h A_{hj} \sum_k A_{hk}, \quad (4)$$

where $n_i$ is the density of ions in the ground state and $\sum_k A_{hk}$ takes into account the relevant transitions between level $h$ and others.

The energy range of the spectral lines allows us to use the linearized cross section, when the collisional excitation occurs due to the high-energy electrons in the tail of the Maxwellian distribution [21]. Here $n(\varepsilon) \propto \exp(-\varepsilon/eT_e)$, where $T_e$ is the electron temperature in electron volt, falls off steeply, so that a linear function can be used for the cross section: $\sigma = C(\varepsilon - E_T)$, where $E_T$ is the excitation potential and $C$ is a constant depending on the specific line. By assuming Maxwellian distribution for the electron energy distribution function the integration of equation (3) using equation (2) gives the following expression for the measured intensity (number of photons per second) of atomic lines:

$$I_a = G_a C_a n_e n_a A_{mn} \sum_l A_{ml} \overline{\sigma}(E_{Ta} + 2T_e)e^{-E_{Ta}/T_e}, \quad (5)$$
where \( \tau_e \) is the electron thermal velocity \( \tau_e = (8kT_e/\pi m_e)^{1/2} \). Similarly, for ionic lines the measured intensity is expressed as follows

\[
I_i = G_i C_i n_e n_i \frac{A_{ij}}{\sum_k A_{hk}} \tau_e (E_{Ti} + 2T_e) e^{-E_{Ti}/T_e}.
\]

Here \( E_{Ta} \) and \( E_{Ti} \) are the upper levels for the most probable lines of argon in infrared (\( \lambda = 810 \) nm, atomic line) and UV (\( \lambda = 350 \) nm, ion line).

### 4. Ion density derivation 1

In order to calculate the ion density in our plasma, we compare the intensities of two groups of lines—ionic \( I_i \) and atomic \( I_a \), which have been taken with two filters, 350 and 810 nm, respectively:

\[
\frac{I_i}{I_a} = \frac{Q_{350}}{Q_{810}} \frac{G_i C_i A_{ij}}{G_a C_a} \frac{\sum_l A_{ml}/A_{mn}}{A_{hk}} \frac{n_i E_{Ti} + 2T_e}{n_a E_{Ta} + 2T_e} e^{-(E_{Ti} - E_{Ta})/T_e}.
\]

The geometric factors for atomic and ionic lines, \( G_a \) and \( G_i \), are assumed the same in our geometry. The constants \( C_a \) and \( C_i \) as well as the factors \( \sum_l A_{ml}/A_{mn} \) and \( A_{ij}/\sum_k A_{hk} \) are not known; however, the product of their ratios can be found from the knowledge of the ratio of intensities \( I_i/I_a \) in the main plasma, where the ion density, \( n_i \sim 10^{15} \) m\(^{-3} \), and electron temperature, \( T_e = 3 \) eV, are known by Langmuir probe measurements. The density of neutrals \( n_a \) at our pressure of 60 Pa equals \( 1.2 \times 10^{22} \) m\(^{-3} \). For the ratio in equation (7) the maxima of the intensity in the main plasma for each spectrum were used. With these parameters the product of the ratios \( C_i/C_a \), \( \sum_l A_{ml}/A_{mn} \) and \( A_{ij}/\sum_k A_{hk} \) is found to be \( 2.8 \times 10^6 \). The photomultiplier tube is characterized by the quantum efficiency, which describes its response to different wavelengths of light. In equation (7) \( Q_{350} \) and \( Q_{810} \) take into account the quantum efficiency at wavelengths of 350 and 810 nm, respectively. In our range of investigations from 350 up to 810 nm the quantum efficiency of our photomultiplier decreases by a factor of 2, \( Q_{350}/Q_{810} = 0.5 \). The only unknown in equation (7) is the electron temperature of the ‘secondary plasma’; however, this is not uncorrelated with the temperature of the first, the ‘secondary plasma’ being embedded in the sheath of the first. The space potential of the ‘secondary plasma’ is lower than the plasma potential of the main plasma and the ‘secondary’ one receives electrons from the first. Ignoring the directed velocity (small w.r.t. the thermal speed) that makes the electrons drift to the rf excited small electrode (grounded in time average), the temperature of the ‘secondary plasma’ corresponds to the high energy part of the distribution of the main plasma. In our pressure range the distribution is Maxwellian, within 10%, so that the hypothesis of almost the same electron temperature in the two plasmas is acceptable. With the above values the higher density in the ‘secondary plasma’ calculated from equation (7) is estimated to be about \( 3 \times 10^{16} \) m\(^{-3} \).

### 5. Ion density derivation 2

The second method to calculate the ion density in the ‘secondary plasma’ is to compare the intensities of the ionic lines (UV spectrum) in the main plasma volume and in the small plasma...
ball’. Here the ratio of the light intensities between two ionic lines from the main plasma volume \(I_{\text{main}}\) and the ‘secondary plasma’ \(I_{\text{second}}\) is:

\[
\frac{I_{\text{main}}}{I_{\text{second}}} = \frac{G}{g} \left( \frac{n_i}{n_i^{\text{second}}} \right)^2. \tag{8}
\]

\(G\) and \(g\) are the geometrical factors for light taken from the main plasma and ‘secondary plasma’, respectively, \(n_i\) and \(n_i^{\text{second}}\) are the ion densities in the main and ‘secondary’ plasmas. As mentioned above, the ion density in the main plasma volume is measured with a Langmuir probe. Under the hypothesis that the electron temperature is not modified in the two plasmas the terms in the upper level for the most probable lines of argon in UV, \(E_T\), cancel out. However, we have to take into account a large difference in geometry between the main plasma and the small ‘secondary plasma’. Hence, it is necessary to calculate the geometrical volumes of the plasma and the ‘plasma ball’, from where the light is collected. In this volume every ‘point’ (infinitesimal element) must be weighted by the fraction of the emission (isotropic) which can reach the tube aperture. The volume of the main plasma from where the light is taken by the photomultiplier tube, is a cone section (see figure 2). Then the geometrical factor for the light taken from the main plasma can be presented as an integral over the plasma dimensions

\[
G = 2\pi \int_{T/2+L}^{T/2+L} \int_{x=0}^{l \tan \alpha} \frac{\pi r^2}{4\pi \left( (l - (T/2))^2 + x^2 \right)} \frac{l}{(l^2 + x^2)^{3/2}} \, dx, \tag{9}
\]

where \(l\) is the integration variable, \(T = 215\) mm and \(r = 0.2\) mm are the length and radius of a photomultiplier tube, \(L = 50\) mm is the plasma dimension, \(\epsilon = 10\) mm is the thickness of a chamber glass plus the plasma sheath and \(\tan \alpha = r/T/2\) (figure 2). Here, \(x\) is a variable which expresses the distance from the axis for any angle \(\alpha\) varying between 0 and \(\alpha\) (the cone angle). The first multiplier presents the fraction of light collected at the tube aperture \(\pi r^2\) from a distance \([(l - T/2)^2 + x^2]^{1/2}\). The factor \(l/(l^2 + x^2)^{3/2}\), also equal to \(\cos \alpha\), takes into account the reduction of the light that can reach the tube aperture because of the incidence at an angle. Since \(x_{\text{max}} = (T/2 + \epsilon + L) \tan \alpha = 0.31\) mm we can always ignore it in the denominator. Then equation (9) reduces to

\[
G = \frac{\pi r^2 \tan^2 \alpha}{4} \int_{T/2+L}^{T/2+L} \frac{l^2}{(l - (T/2))^2}. \tag{10}
\]

This integral is solved analytically and equation (10) gives \(1.3 \times 10^{-4}\) mm³.

The volume of the light from the small ‘secondary plasma’ was calculated as a volume of a cylinder (approximation to a small section of a cone, see figure 4). This cylinder has a radius equal to \(R' = (T/2 + \epsilon + L/2) \tan \alpha\). The height of this cylinder is equal to the diameter of ‘secondary plasma’ \(D = 2r_g\):

\[
g = \pi \left( \frac{T}{2} + \epsilon + \frac{L}{2} \right) \tan^2 \alpha 2r_g \frac{\pi r^2}{4\pi ((L/2) + \epsilon)^2}. \tag{11}
\]

\(r_g\), the radius of this glow, changes depending on the position above the lower electrode. It decreases from 2 mm on the electrode to 0 at the top of the small glow at a height \(h = 4.5\) mm. The shape of the ‘secondary plasma’ is schematically represented by a half ellipse with a major radius 4.5 mm and a minor radius 2 mm. The radius \(r_g\) which is used in equation (11) was calculated from the equation of ellipse in each point of scanning. The last term in equation (11) is the weighting factor; the light is emitted isotropically from the small secondary plasma is caught on the tube aperture proportionally to the solid angle covered.

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Figure 4. Sketch of the apparatus for the spectroscopic measurements in the ‘secondary plasma’. PMP is photomultiplier, $T$ and $r$ are the length and the radius of the additional tube, $L$ is the plasma dimensions, $\varepsilon$ is the thickness of the chamber glass plus the plasma sheath, $R'$ is the radius of the cylinder which presents the taken light. (Not to scale.)

Thus, the maximum of the geometrical factor ratio $G/g$ equals 20. The maximum calculated density of ‘secondary plasma’ is of the order of $2.66 \times 10^{16} \text{m}^{-3}$, which is in good agreement with previous calculations. We note here that the first method is more robust against small dishomogeneities in the electron temperature. Comparing equation (7) in the main plasma and the same equation in another plasma with a different temperature, $T'_e$, gives rise to an exponential factor $\exp\left(-\frac{(E_{T_i} - E_{T_a})(T'_e - T_e)}{T'_e T_e}\right)$ for the first method and, using equation (8) gives the factor $\exp\left(-\frac{(E_{T_i})(T'_e - T_e)}{T'_e T_e}\right)$ for the second method.

6. Density profile in the ‘secondary plasma’

Using the above intensity data we can build the density profile in the ‘secondary plasma’ and compare it with the position of our clusters in order to know more precisely the parameters of the plasma surrounding the clusters. Since the scanning of the ‘plasma ball’ gives us eight points, with a scanning step of 0.5 mm, the density was derived for each point of the corresponding collection volume of the small glow. The density profile is shown in figure 5. The vertical lines indicate the mean position of the clusters. It is clear that the clusters are situated around the maximum of the density. Hence, we can conclude that the density of the ‘plasma ball’, which surrounds our clusters, equals the averaged density estimated from the spectroscopic analysis $\approx 2.8 \times 10^{16} \text{m}^{-3}$.

7. Theoretical calculation of the ‘plasma ball’ density profile

The density profile of the ‘secondary plasma’ can be obtained analogously to the analysis of the positive column, which was carried out by Schottky and presented by Cobine [22]. The calculations were performed for the collisional regime using the ambipolar diffusion coefficient. To estimate collisionality we compared the dimensions of the system with the mean free path of ions in argon $\lambda = 1/n_a \sigma$, where $n_a$ is the density of the atoms and $\sigma$ is the cross section for the collisions in argon, which was measured using ion cyclotron resonance by Wobshall et al [23]. For a low ratio of the electric field to the pressure, $E/p$, with the energies at or near thermal, $\sigma = 2.15 \times 10^{-18} \text{m}^2$. At 60 Pa the mean free path for ions is estimated to be $32 \mu\text{m}$. Thus, the
Figure 5. The dashed curve represents the profile of the density from the first theoretical model, equation (18), the solid curve represents the density profile from the second theoretical model, equation (24), and the curve with squares represents the experimental density profile \( y' = n/n_{\text{Max}} \) and \( x' = x/h \), where \( h \) is the height of the ‘secondary plasma’. Two vertical lines show the upper and lower borders of the plasma clusters.

ratio of the small glow dimensions and of the mean free path is 140, giving a strongly collisional case.

Hence, we can use the collisional model described in [22]. The plasma is considered to be quasi-neutral, i.e. \( n_e = n_i = n \). The flux of ions moving toward the wall by diffusion is

\[
nv = -D_a \nabla n,
\]

where \( D_a \) is a coefficient of ambipolar diffusion and \( v \) is the ion rate. In order for the plasma concentration to remain in equilibrium, the ion flux should be compared with the number of electrons, which take part in ionization

\[
\nabla \cdot (nv) = Zn,
\]

where \( Z \) is the number of ionizing collisions per second made by each electron.

Combining these two equations we obtain

\[
\nabla^2 n + \frac{Zn}{D_a} = 0.
\]

In the case described by Cobine [22] calculations were performed for a portion of cylindrical discharge tube, while we have a ‘plasma ball’ of spherical shape. We consider a portion with radius \( r \) of a spherical shell of radius \( R \). Thus, for the spherical case equation (14) should be written as follows:

\[
\frac{d^2n}{dr^2} + \frac{2}{r} \frac{dn}{dr} + \frac{Zn}{D_a} = 0.
\]

By substituting \( r = \sqrt{D_a/Zx} \) we obtain the following equation

\[
\frac{d^2n}{dx^2} + \frac{2}{x} \frac{dn}{dx} + n = 0.
\]
The solution of such an equation is the spherical Bessel function of the first kind $j_m(x) = \sqrt{\frac{x}{2}} J_{m+1/2}(x)$. For the case $m = 0$ the solution is the zero order Bessel function $j_0(x) = \sin x / x$ and $n_r = n_0 j_0(x)$. $n_0$ is the concentration of ions at $r = 0$. This function approaches zero when $x = \pi$, which corresponds to the radius of a sphere $R$:

$$x_R = R \sqrt{\frac{Z}{D_a}} = 3.1415. \quad (17)$$

Thus, the density distribution is found to be

$$n_r = n_0 \frac{\sin(\pi r / R)}{\pi r / R}. \quad (18)$$

Since, the density distribution in our ‘secondary plasma’ is described by the function $\sin x / x$, we can compare the behavior of this function with the density profile obtained from the experimental measurements of the intensity. In figure 5 the function $\sin x / x$ is shown together with the density profile in the ‘plasma ball’. One can see that the behavior of these two curves is very similar.

In our small ‘plasma ball’ the distribution of ions and electrons is radial, therefore for the analysis of the ‘secondary plasma’, we can estimate the flux of ions from the center out. The ion flux proportional to the ion density integrated over the volume of our sphere with radius $R$ is

$$J_i = 4 \pi R^2 D_a \left( \frac{dn}{dr} \right)_{r=R}. \quad (19)$$

We already found the density distribution to be $n = n_0 \sin x / x$. From this dependence by integration at $x = \pi$ the ion flux is obtained as

$$J_i = 4 R^2 n_0 \sqrt{Z D_a}. \quad (20)$$

From equation (17), we have $D_a = R^2 Z / \pi^2$. Then the ion flux can be presented as

$$J_i = \frac{4}{\pi} R^3 n_0 Z. \quad (21)$$

Another approach to find the density distribution, which differs from the first one, is to assume that the number of ionization $Z n$ is a constant in a volume and does not depend on the distance from the center; then $\nabla (n v) = C$. In that case our model should be described by the equations:

$$n v = -D_a \nabla n, \quad \nabla \cdot (n v) = C. \quad (22)$$

From these equations for the spherical ball we have

$$\frac{1}{r^2} \frac{d}{dr} \left( r^2 \frac{dn}{dr} \right) + \frac{C}{D_a} = 0. \quad (23)$$

After integration the density is expressed as follows:

$$n_r = n_0 \left[ 1 - \frac{C}{6 D_a n_0} r^2 \right]. \quad (24)$$

The flux of ions at $r = R$ equals to $J_i = 4 / 3 \pi R^3 C$. If $n = 0$ constant $C = 6 D_a n_0 / R^2$.

The behavior of the density profile from this model is also shown in figure 5. It describes the experimental density profile even better than the previous model, although we do not have any evidence to assume the ionization to be constant in the ‘plasma ball’.
8. Conclusion

This work presents results of the spectroscopic analysis of the 3D plasma cluster environment, a plasma of very small size. Spectroscopic analysis was chosen as the only possible non-invasive method. Using the steady-state corona model and the calculation of the geometrical volumes of the main and of the ‘secondary’ plasmas the density of the small plasma was obtained. This fact is fundamental for future plasma cluster investigations, since it gives us the possibility to estimate the screening Debye length in the plasma and, hence, the scaling of the distance between particles in the clusters, which defines the cluster structures. Electron losses on particles of $3.4\mu m$ diameter are always too small to modify the density distribution. The density profile obtained using the data of discharge intensity helps us to estimate more correctly the plasma density near the clusters. Besides, the density distribution is compared to the results of two theoretical models built on the principles of ion collisional motion. Both theories are within the absolute errors of our measurements, here estimated to be about 22% (the main uncertainty being the estimation of the electron temperature of the small plasma). However, when we analyze the profile of the density (figure 5), we see that the constant ionization model has a larger distribution which falls also within the relative errors of the measurements that was estimated 8% (the main uncertainty being the nonlinearity of the measured plasma density within the resolution range). Higher resolution would be needed to explain the 3D electromagnetic configuration that induces extra ionization in the plasma ball and in the region directly adjacent to the electrode, hardly visible in figure 1. The main results of this paper are performed for a very specific type of experiment but could be of more general interest. The developed method, in particular when associated with an independent determination of the electron temperature, can be useful to characterize small plasma regions in many plasma devices outside the dusty plasma community.

Acknowledgments

We thank Herr Steffes for continuous assistance. This research was founded by Das Bundesministerium für Bildung und Forschung durch das Zentrum für Luft- und Raumfahrt e.V. (DLR) unter dem Förderkennzeichen 50 JR 0582.

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