The plasma-sheath boundary near the adaptive electrode as traced by particles

B M Annaratone¹, M Glier¹,², T Stuffer¹,², M Raif¹,², H M Thomas¹ and G E Morfill¹
¹ Centre for Interdisciplinary Plasma Science, Max-Planck Institute für Extraterrestrische Physik, Postfach 1312, D-85741 Garching, Germany
² Kayser-Threde GmbH, 48 Wolfratshauser, D-81379, München, Germany
E-mail: bma@mpe.mpg.de

New Journal of Physics 5 (2003) 92.1–92.12 (http://www.njp.org/)
Received 18 February 2003, in final form 28 May 2003
Published 14 July 2003

Abstract. The adaptive electrode consists of a two-dimensional array of single electrodes each individually voltage controllable to produce local modifications in the plasma edge. This paper presents an experimental study on the nature of the perturbation introduced by the DC biasing of the pixels, using suspended particles as tracers. The particles above a negative pixel show an expansion of the sheath but for high negative voltages the particle can no longer levitate. This is explained by the reduction of the RF enhancement of the charge on the particle. Under certain conditions the sheath above a positive pixel evolves into multiple double layers, setting up a negative pre-sheath far into the plasma.
1. Introduction

Laboratory plasmas are easily modified by any perturbation that might appear on the boundary. All the surfaces surrounding the plasma are in a delicate electric equilibrium due to the dynamical balance of the fluxes of charged particles. The segmented, ‘adaptive’ electrode is a powerful tool for introducing local modifications of the sheath. These modifications, both steady state and time modulated, are often employed in plasma processing. A spatially resolved control of the collected species, electrons and ions, and of their energy, offers a variety of applications that range from modulated etching depth, to the control of the degree of crystallization of deposited layers and to selected powder deposition and consequent doping through powder sputtering.

Small particles of micrometre size, suspended in the plasma sheath, are particularly sensitive to sheath non-uniformity. Nanosized particles settle in the plasma but particles of diameter above about 1 μm enter the electric field of the sheath edge. These particles are often unwanted in many technological discharges but are added to the discharges on purpose for fundamental studies on complex plasmas. The various forces on these particles, including gravity and ion drag, are counterbalanced by the electrostatic forces because of the dynamical charge, which forms on the particles. Any alteration of the electron and ion fluxes to the external electrode’s surface also modifies the fluxes to the suspended particles so that they are a very sensitive instrument to monitor the sheath behaviour. The study of the plasma sheath using suspended particles above electrode voltage discontinuities is the main object of this paper.

2. Experiments

We report on experiments performed using a prototype adaptive electrode, which consists of 57 square pixels, independently driveable in DC and RF, and four external areas in the shape of a surrounding ring. The square pixels have dimensions of $3.81 \times 3.81 \text{ mm}^2$; one of them has been divided into nine sub-segments used to study the effect of a smaller biased area. The full arrangement of the pixels is shown in figure 1. This adaptive electrode has been installed as the lower electrode of a parallel plate discharge where the upper electrode is RF driven. In this paper only a large and a small pixel are DC driven while all the others have been left floating. The plasma chamber where these experiments have been performed, called the PKE-Nefedov
Pixel 59...61 used as confining ring

**Figure 1.** Schematic diagram of the ‘adaptive electrode’ and the pixels’ distribution.

**Figure 2.** The PKE-Nefedov chamber.

chamber, has been described in [1] and it is shown in figure 2. Melamine formaldehyde particles, of 6.4 µm diameter, were injected in the plasma using a dispenser placed in the middle of the upper electrode (RF driven as the surrounding electrode). The position/motion of the particles in the plasma sheath was visualized by illuminating the particles with a laser, fanned out in a vertical plane, and recorded with a video camera from the side.
2.1. Visualization of the sheath

Measurements were aimed in visualizing the unperturbed plasma-sheath boundary above one biased pixel. Only a few particles were introduced into the chamber at one time and the experiment was filmed from the side for about 1 minute. The visualization of the sheath-edge profile was obtained by overlapping up to ten frames taken at time intervals when the few non-interacting particles had moved sufficiently far from the original position. Data were taken for a driving RF (13.56 MHz) voltage on the electrodes of 140 and 200 V (peak to peak) and for pressures at 5, 10, 50 and 100 Pa using a large and a small pixel. Figure 3 shows the profiles obtained at $p = 10$ Pa and a RF voltage applied to the upper electrode of $V_{RF} = 140$ V with a large pixel, in the centre, biased in DC as indicated. Each picture shows an area of $23 \text{ mm} \times 12 \text{ mm}$ after image frame manipulation. Figure 4 has been taken in similar conditions but with $p = 50$ Pa. The injected particles settle in an electric field, which multiplied by the acquired charge balances the resultant of the other forces including gravity. The charge of the particles in the plasma sheath has been measured by several methods [2]–[4]. Following the paper of Tomme et al [4] we estimate an average charge of the particles. To give an example, the charge on each particle is about $6170e$ at 10 Pa, which corresponds to an electric field in the vertical equilibrium of $1640$ V m$^{-1}$ (the ion drag is in general recognized as small in the above references).
2.2. Negatively biased pixel

The particles around a negatively biased pixel expand almost spherically into plasma. At 10 and 50 Pa particles are in equilibrium in the upper part of the hemisphere. In figures 3 and 4 some residual interaction is possible, e.g. where we can identify some ‘chains’. Certainly some isolated particles are seen in equilibrium above the centre of the pixel and in the upper, lateral side. In this latter case the condition for horizontal equilibrium means that the outward component of the electrostatic forces must be balanced by another force with an equal component inward. At lower pressures, 5 Pa, or higher pressures, 100 Pa, there are no equilibrium positions higher than the unperturbed distance from the electrode and the particles are just pushed away by the negative bias of the pixel, forming a void circle.

2.3. Positively biased pixel

All the frames used to form figures 3 and 4 have been taken in steady-state equilibrium, although, during the increasing of the bias from one step to another, some particles have fallen onto the
The bright plasma region and the high density particle region. The laser light trace on the electrode is 11.6 mm long. The high density region appears reflected on the electrode. The bright region, the upper glow, is constricted in the lower part, just above the high density region, by the electrode RF sheath.

electrode. With reference to figure 4, when the pixel bias is positive with respect to ground but negative with respect to plasma potential, the particles approach the pixel through a narrow channel, much smaller than the pixel size. Clearly, the floating sheath of the neighbouring pixels is in part overlapping the space in front of the biased pixel. At $V_{DC} = 15$ V, approaching the plasma potential, a double layer is established where the electrostatic field suitable for levitation is pushed away from the electrode. For $V_{DC}$ between 35 and 40 V a bright glow appears. The electron current is channelled through the bright region to a small region in which the field is inverted and there are conditions for high-density particle levitation. The dense region only covers a fraction of the biased area (perhaps because of insulating particles already dropped on the pixels). An enlarged photo is shown in figure 5. In this figure the filter which normally screens away the plasma glow has been removed and it is possible to see the bright plasma region and the high particle density region in which a convective motion of the particles, down in the central part and up outside, has been observed. On decreasing the positive voltage on the pixel most of the particles return to previous positions.

2.4. The small area pixels

The above experiments have been repeated using the smaller pixels, 1.28 mm side. At 5 Pa the sheath thickness is much larger than the dimension of the pixel and the voltage applied does not modify the equilibrium position of the particles levitating above. The plasma boundary is affected only when the pixel linear dimension approaches the sheath thickness, i.e. $l_{\text{pixel}} > 10\lambda$. At 10, 50 and 100 Pa the particles might find equilibrium in a thick vertical region above the electrode, the lower particles being at the unperturbed level. Only at $p = 100$ Pa, $V_{RFpp} = 140$ V and $V_{DC} = +80$ V does a narrow bright region appear; see figure 6.
3. Discussion

3.1. Negative biased pixel sheath

The vertical equilibrium position of the particles in the centre of the pixel is shown in figure 7. If the relative position of a particle and the plasma is unmodified by the pixel’s voltage the charge of the particle should be constant. The paper of Tomme et al [5] states that a particle-free sheath above a plane electrode, in DC and RF plasmas, is, to a high approximation, parabolic. If we can assume a constant charge the equation describing the system would be

$$V_{\text{plasma}} - V_{\text{pixel}} = \frac{1}{2} k (x_{\text{particle}} + x_{\text{pp}})^2$$

where $x_{\text{particle}}$ is the position of the particle from the electrode and $x_{\text{pp}}$ is the distance from the particle to the quasi-neutral plasma. The derivative of equation (1) calculated at the position of the particle, $E = k x_{\text{pp}}$, is known from the levitation condition, $qE = mg$, and the charge [4], allowing us to reduce the number of degrees of freedom by one.

Figure 8 shows the two terms of equation (1) for $p = 5$, 10 and 50 Pa and the driving voltage $V_{\text{RFpp}} = 140$ V. Here the value of the plasma potential has been found from the zero-intercept condition (and it is in good agreement with Langmuir probe results). $k$ has been varied to obtain the best fit. From the quality of the fit of the curve at 10 Pa we can assume constancy of $x_{\text{pp}}$ so that on a large range the charge on the particles is unmodified by the expansion of the sheath. At 5 and 50 Pa this assumption is no longer valid. Already for small negative voltage the particle’s distance from the plasma increases; this means a higher electric field and lower charge. Soon after there are no more conditions for levitation. Similar behaviour has been seen for $V_{\text{RF}} = 200V_{\text{pp}}$. It should not be attributed to the limited extension of the pixel and the

Figure 6. Particles in front of a DC biased ‘small’ pixel, $p = 100$ Pa and $V_{\text{RF}} = 200V_{\text{pp}}$. Picture size $23 \times 12$ mm.
non-planarity of the sheath, because a similar effect, in which particles do not levitate below a certain negative DC voltage applied to a large electrode, has been observed by Ticos [6].

The observed variation of charge has been related to the reduction of the RF contribution to the sheath. Melando et al [7] calculated the charge of a particle in an RF sheath. The floating potential, $U_{DC}$ (defined with respect to the local space potential $V_0$), is defined by the following equation.

$$\sqrt{\frac{8m_e}{\pi m_e}} \exp\left(\frac{eV_0}{kT_e}\right) \exp\left(\frac{eU_{DC}}{kT_e}\right) I_0\left(\frac{eV_0}{kT_e}\right) = \left(1 - \frac{2eU_{DC}/kT_e}{1 - 2eV_0/kT_e}\right).$$ (2)

Here $V_o$ is the RF voltage difference between the plasma and the position of the particle and $I_0$ is the zeroth-order modified Bessel function of the first kind. The charge derived from this floating potential using the vacuum capacity is higher than that acquired in a DC sheath. The second term in equation (2) has been derived in the hypothesis of orbital motion for the ions, which is not completely applicable in the range of pressure considered in this paper [8]. But, however

---

**Figure 7.** Position of the particles in the centre of the pixel versus the applied voltage.

**Figure 8.** Plot to check the condition for a parabolic profile of the voltage above the centre of a biased pixel. The abscissa represents the first term of equation (2), the ordinate show both terms of equation (2).
the ion motion is described, the first term of equation (2) shows a dependence on the RF voltage and the negative charge acquired by the particle is enhanced.

In our experiments the expansion of the sheath above a negatively biased pixel reduces the plasma-electrode capacity. The amplitude of the RF voltage on the pixel, for $p = 6.7$ Pa and $V_{RFpp} = 300$ V on the electrode, has been plotted versus the DC bias (see figure 9) with the electrical connection as in figure 10. In this figure $C_s$ represents the capacity of the plasma sheath above a floating pixel and $RC_s$ is the modified capacity above the biased pixel. There are 6 pF between two pixels with a side in common (much less between two pixels with a corner in common). $4C_s$ represents the capacity of the four nearby pixels and $C_c$ is hence 24 pF.

Every pixel has a capacity to ground, $C_a$, of 24 pF, which includes the capacity of the oscilloscope probe. $C_b$ has been taken as $4C_a$. We also assume that the sheath capacity is much smaller than the other capacities involved. With these data $R$, the reduction in the sheath capacity due to biasing, can be derived. To give an example, at $-100$ V DC we have 314 mV over $C_a$ and 350 mV over $C_b$. $R$ is 0.77. Although these measurements bear a large error, primarily due to the presence of a strong second harmonic, intrinsic in an almost symmetric system, they suggest a gradual reduction in the RF current through the sheath when a negative DC voltage is applied. The charge on the particle is accordingly also reduced [7] until the particle falls down.
In certain situations particles cannot be above the centre of the pixel but are in equilibrium on the side; see for example the bias $-80$ V in figure 4. In this case, as for the particles levitating in the side of the hemisphere co-existing with particles in the centre (see $-60$ V in figure 3), a force must balance the horizontal component of the electrostatic forces. Contrary to intuition the surfaces outlined by the particles cannot coincide with the equipotential surfaces. The ion drag, small in all the above quoted references, could be assumed parallel to the electrostatic forces in a highly collisional sheath, say at 100 Pa, with a mean free path for ions in argon about 20 $\mu$m, or more vertical than the electrostatic forces at lower pressures, because the velocity of the ions is acquired from the plasma.

3.2. Positive biased pixel sheath

The sheath above a positively biased pixel is a complex phenomenon, which can only be understood in part by this particle-tracing method. A good insight can be given by the comparison with the DC discharges at the anode [9] or in front of a constriction [10]. A plasma sack forms when the velocity of the electrons tends to overcome the thermal velocity, i.e.

\[
I_e > \frac{An_0C\nu}{4}.
\]

The boundary of this localized glow is a double-layer sheath with an inner positive-ion space charge and an outer electronic space charge. The extended negative pre-sheath attracts particles far away in the plasma. When the bright region appears the RF current to the pixel decreases, the jump is shown in figure 9, $V_{DC} = 40$ V. The DC bias of the driven electrode starts to decrease in magnitude (see figure 11), showing that the plasma potential is dragged more positive and the capacities of all the plasma boundaries are modified. Another double layer with inversion of the field is revealed by the suspension of the particles very near to the electrode. The high particle density region appears at a pixel voltage higher than the ionization energy above the plasma potential, here between 15 and 20 V, so that the accelerated electrons boost the ionization rate. This explains the stability of the system in the most positive region of the discharge. In order to maintain a charge constant in time the particles should receive a constant flux of ions as well as of electrons. The particle separation is about 30 $\mu$m and should give us an indication of the local electron Debye length. A qualitative schematic of the voltages in front of a biased pixel is shown in figure 12.

4. Conclusion

We have described the steady state equilibrium position of isolated particles in front of an adaptive electrode. The equilibrium position of the particles above a negative electrode depends strongly on the RF current circulating across the local sheath. It is well known that the application of an RF voltage to the plasma boundary induces a DC bias; see for example [11]. In this paper we have proved that the application of a DC voltage to a surface affects the local RF current. The average electron density in the RF sheath is much larger than in the equivalent DC sheath, although, due to the dominant ion charge, the voltage profile is not much affected. The charge acquired by a particle suspended in the sheath decreases with the increasing thickness of the sheath, because of the reduction in the RF contribution, until it is insufficient for levitation. This effect is general but difficult to foresee in different reactors. Important parameters are the
Figure 11. The DC bias on the driven electrode versus the DC voltage applied to the pixel.

Figure 12. Schematic of the double layers. The thick line shows the position of the electric field suitable for levitation in case of constant charge on the particles.

symmetry of the system and the ratio of the biased electrode to the other possible surfaces for the return of the RF current.

The profiles outlined by the particles should by no means be identified with the equipotential surfaces. At the moment it is still unclear how the side component of the electrostatic forces is compensated. We have already seen why the ion drag is not the required solution. Any thermophoresis due to the pixel being heated by ion bombardment would push the particles away. One possibility is asymmetric ion drag. Another possibility would be a force due to the gradient in the electron density. Secondary electrons might also play a role.
The particles in front of the positive electrode have revealed an unsuspected inversion of the field. More work is required to study the extremely high density of the particles in the bright region and the observed convective motion.

This paper cannot provide the full comprehension of all the observed effects but certainly proves that the tracing particle method is a powerful diagnostic. Moreover, it proves that the plasma boundary can be manipulated to fulfil applications’ requirements on a length scale comparable with the Debye length.

Acknowledgments

We would like to thank Professor J E Allen for useful discussions and one of the referees for suggesting an important contribution. This research was funded by Das Bundesministerium für Bildung und Forschung durch das Zentrum für Luft-und Raumfahrt e.V. (DLR) unter dem Förderkennzeichen 50 RT 0207.

References

[1] Rothermel H, Hagl T, Morfill G E, Thoma M H and Thomas H M 2002 Phys. Rev. Lett. 89 175001
[2] Konopka U, Morfill G E, Thomas H M and Ratke L 1998 AIP Conf. Proc. 446 53
[3] Homann A, Melzer A and Piel A 1999 Phys. Rev. E 59 R3835
[4] Tomme E B, Annaratone B M and Allen J E 2000 Plasma Sources Sci. Technol. 9 87–96
[5] Tomme E B, Annaratone B M and Allen J E 2000 Phys. Rev. Lett. 85 2518
[6] Ticos C 2003 Private communication
[7] Melandso F, Nitter T, Aslaksen T and Havnes O 1996 J. Vac. Sci. Technol. A 14 619
[8] Annaratone B M, Allen M W and Allen J E 1992 J. Phys. D: Appl. Phys. 25 417
[9] Langmuir I 1929 Phys. Rev. 33 954
[10] Andrews J G and Allen J E 1971 Proc. R. Soc. A 320 459
[11] Annaratone B M, Glier M, Raif M, Stufller T, Thomas H and Morfill G E 2003 Int. Conf. on Plasma and Ionised Gases (Greifswald, Germany, July 2003)