THE INFLUENCE OF COLLISIONS ON THE ION CURRENT TO AN ELECTROSTATIC PROBE

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Abstract

The Monte Carlo simulation of the motion of Ar^+ ions in the space charge sheath surrounding a cylindrical Langmuir probe has been carried out. From these simulations the ion currents to the probe have been calculated.

1. Introduction

Electrostatic probes are widely used to determine electron number densities, electron temperatures and electron energy distribution functions in gaseous plasmas. The most accurate approach to the determination of the above-mentioned quantities is based on the so–called orbital motion limited current (OMLC) theory [1].

It is also possible, in principle, to determine the positive ion number density, n_+, in a plasma using the OMLC theory for a negatively biased probe. However, it has been known for a long time that the value of n_+, derived in this way exceeds the electron number density, n_e, under most conditions [2, 3] an unacceptable result in quasineutral plasmas. Recent measurements of ion probe currents collected by a probe have been carried out in flowing–afterglow/Langmuir probe (FALP) apparatus at Innsbruck [4]. In this experiment afterglow plasmas were created composed largely of Ar^+ ions with electrons in He carrier gas. All components were in thermal equilibrium at a temperature $T = 300$ K, and the pressure of the carrier gas was 1.2 Torr. Electron and ion current were measured to a cylindrical probe, radius $r_p = 25$ μm, length $l_p = 4$ mm.

We have carried out Monte Carlo simulation of the motion of ions in the sheath for the plasma conditions of these FALP experiments and thus we have computed the ion currents to the probe.

2. Theoretical model

The motion of ions which undergo collisions with neutrals in the space charge sheath around a probe can be simulated using Monte Carlo method by considering a great number of individual ion trajectories. The trajectories of the ions are treated one by one following their entry into the space charge sheath until the ions escape from the sheath or until they are captured by the probe.

For the space charge sheath radius, r_s, we adopt the simple expression by Bettinger and Walker [5]:

$$r_s^2 = r_p^2 + \frac{\pi \lambda_d^2 \eta \sqrt{1 + 2\eta/3}}{\ln\left(\frac{r_s}{r_p}\right)} , \tag{1}$$

where $\eta = e|U_p|/kT$ is the normalized probe voltage and λ_d is the Debye length. We assumed that beyond r_s the plasma is not disturbed by the probe potential which is completely contained within the sheath. The ions start from the sheath boundary with a Maxwellian velocity distribution appropriate to a $T_+ = 300$ K.

It is considered that the cross section for elastic collisions between Ar^+ ions and He atoms varies inversely with the relative velocity of the Ar^+ ion and the He atom:

$$\sigma(v) = \frac{\sigma_0 v_0}{v} \tag{2}$$

in accordance with the Langevin–Gioumous–Stevenson model [6, 7] where $\sigma_0 = 1 \times 10^{-14}$ cm^2 is the value of the cross section at $v_0 = 432.8$ ms^{-1} (the mean square velocity of Ar^+ relative to He atoms at $T = 300$ K) [8].

The trajectory of an ion between two successive collisions is obtained from the classical mechanics equations. In this simulation we treat the probe as an infinite cylinder. For the variation of the potential $U(r)$ with the distance from the centre of the probe, r, we adopt the simple analytical formula derived by Chen [9]:

$$U(r) = a\left(\sqrt{r_s^2 - r^2} - r_s \ln\left(\frac{r_s + \sqrt{r_s^2 - r^2}}{r}\right)\right) . \tag{3}$$

The boundary conditions are that $U(r) = 0$ at the sheath boundary and $U(r) = U_p$ at the probe surface. The constant a is calculated from these boundary conditions.

3. Results

Sample ion trajectories modelled at the fixed probe voltage $U_p = -2$ V for electron number density $n_e = 5 \times 10^8$ cm^{-3} are shown in Fig. 1 under collisionless conditions and when collisions occurs.

Clearly, the trajectories are influenced significantly by collisions in the sheath, and the simple OMLC theory approach cannot be applied when collisions occur. The ions that escape from the sheath do so mostly due to scattering collisions in the outer region of the sheath. If the ion collides with neutral atom deeper in the sheath or if the ion collides many times, it loses too much of its kinetic energy to be able to escape from the potential well around the probe and it has to end up at the surface of the probe.

The number of ions collected by the probe is recorded during the simulation, and the percentage, p, of the ions that cross the sheath boundary which are collected by the probe is calculated. The p obtained for several different electron number densities at a fixed U_p of -2 V are plotted in Fig. 2 together with the p obtained by modelling of the collisionless case for the same sheath radii.

The important result is that the collisions increase p as can be seen immediately. Only at pressures higher than 10 Torr falls p below p_{omlc}, see Fig. 3, where the p obtained for several different neutral gas pressures at a fixed U_p of -2 V and $n_e = 5 \times 10^8$ cm^{-3}, are plotted. The data in Fig. 3 were calculated for $r_p = 13.5$ μm. The simulations with the probes with different radii (13.5 μm and 25 μm) give almost the same percentage of ions collected by the probe. Because the sheath radius at $\lambda_d \gg r_p$ depends only weekly on the probe radius, the ion current almost does not depend on the probe radius.

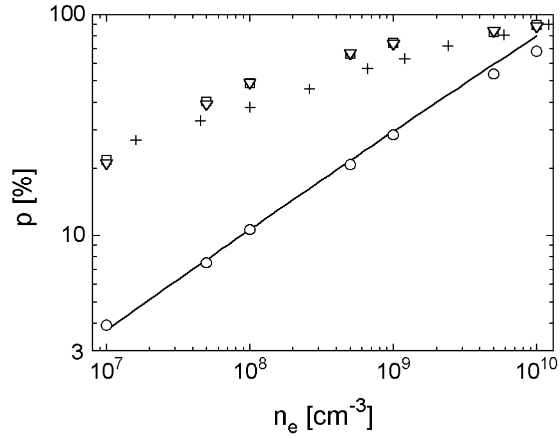

Fig. 2. The percentage of the ions entering the sheath, p, that are collected by the probe versus electron number density at $U_p = -2$ V. The squares and triangles are the values calculated from the Monte Carlo simulations with collisions, the circles are the values calculated from the simulation without collisions and the crosses are the experimental data points from [4]. The line is the ratio of the current predicted by OMLC theory and random thermal current crossing the sheath boundary.

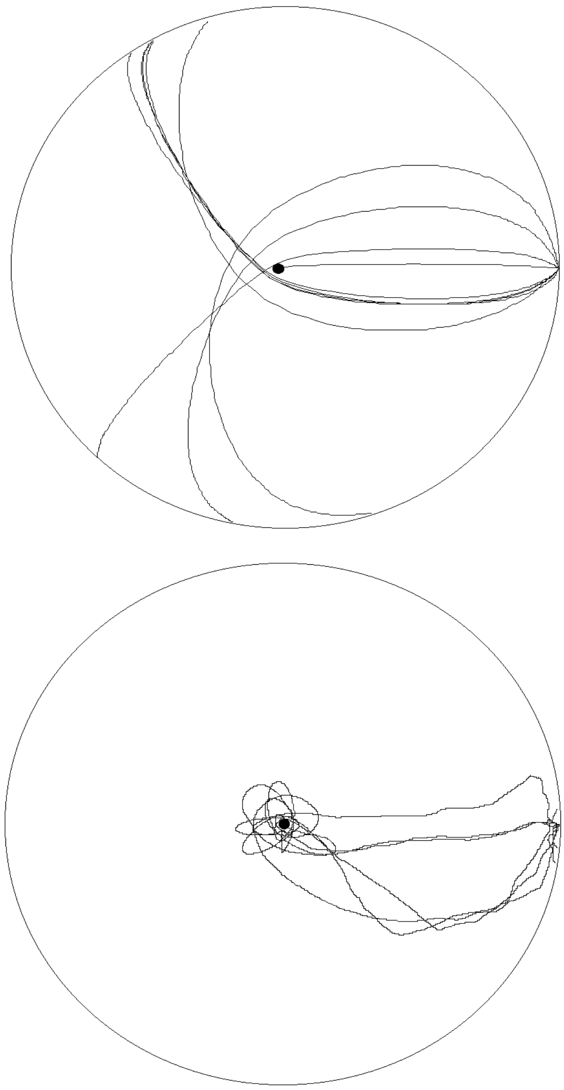

Fig. 1. Ten ions trajectories at $U_p = -2$ V. Upper figure shows trajectories without collisions, lower figure with collisions. Electron number density is $n_e = 5 \times 10^8$ cm^{-3}. The ions start from the sheath boundary (marked by the circle with radius r_s) with a Maxwellian distribution of velocities ($T_+ = 300$ K).

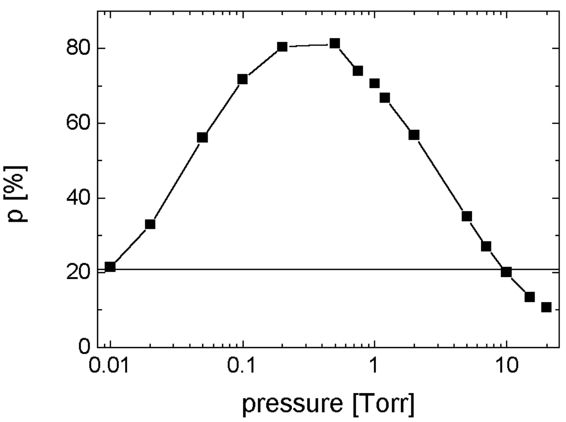

Fig. 3. The percentage of the ions entering the sheath, p, that are collected by the probe versus gas pressure at $U_p = -2$ V. Cylindrical probe, radius $r_p = 13.5$ μm, length $l_p = 4$ mm, ion number density $n_+ = 5 \times 10^8$ cm^{-3}, ion temperature $T_+ = 300$ K. OMLC theory predictes $p = 21$ % (indicated by horizontal solid line).

The ion current to the probe, i_+, can then be calculated as the product of p and the random ion current crossing the sheath boundary thus:

$$i_+ = \frac{1}{4} A_s n_+ \sqrt{\frac{8kT_+}{\pi m}} \cdot \frac{p}{100} \ , \qquad (4)$$

where A_s is the surface area of the sheath which is $2\pi r_s l_p$ for cylindrical geometry (r_s is given by eq. (1)).

The simulations show that collisions enhance i_+ above that $i_{+_{omlc}}$ predicted by OMLC theory. Because the p under the actual experimental conditions are higher than those p predicted by OMLC theory, the n_+ derived using OMLC theory will be correspondingly falsely higher than n_e (see[3]).

More details about the simulation and the results can be found in [10].

Acknowledgement

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