Potential formation in a magnetized inductively coupled plasma

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Abstract: The potential formation in an inductively coupled plasma device in uniform magnetic field, at moderate pressures, is experimentally discussed. The axial profiles of plasma parameters showed that this double layer appears inside the plasma source as a natural border between two plasmas with different properties.

Key words: Inductively coupled plasma, electric double layer

1. Introduction

Potential formation are one of the big topics in plasma physics. Recently, the existence of current-free potential double layers in helicon discharges at rather low pressures (*i.e.* less than 1 mTorr) has been reported [1]. Although some progress has been made in double layer characterization in an RF discharge [2], the physical basis of its emergence is still not established.

The aim of this paper is to report on new experimental data on double layer appearance in magnetized inductively coupled plasma at moderate pressures (*i.e.* greater than 1 mTorr), at which it was asserted that such potential structures do not form [1] and to establish the phenomenology underlying their emergence.

2. Experimental device and results

The experiments were carried out on a magnetized inductively coupled plasma device, illustrated in Fig. 1. The plasma is produced in a glass tube T, surrounded by a helical antenna A. The glass tube is mounted at one end of a stainless steel cylindrical vessel, which is the main chamber of the device. The whole system is surrounded by magnetic coils that produce a uniform axial magnetic field, with a measured magnetic induction $B = 217 \pm 3$ G.

An Al disc collector C, facing the glass tube T, controls the processes inside the plasma. The plasma properties were axially measured with an RF compensated Langmuir plane probe (P in Fig. 1), moved between $z = -11$ cm and $z = 8$ cm.

The measurements were performed using Ar as a working gas, at a moderate pressure ($p = 2$ mTorr). The RF input power was 200 W, with less than 0.5% reflection, at the working frequency of 13.56 MHz. Throughout this experiment the collector position was fixed downstream, axially, at $z = 30$ cm and positively biased with respect to the ground ($V_c = 10$ V).

The axial profile of the plasma potential in the probing domain is plotted in Fig. 2. It shows that after an important increase inside the glass tube (*i.e.* upstream or $z < 0$), the plasma potential saturates downstream (*i.e.* $z > 0$) at about 32 V. These two distinct regions are connected by a potential wall with the height $\Delta V_s \approx 7$ V, located at $z = 0$ (*i.e.* at the border between upstream and downstream).

The electron temperature profile, represented in Fig. 3, although has a general decreasing trend, displays a local

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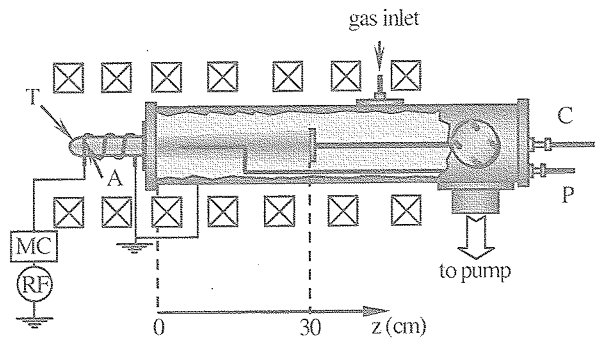

Fig. 1 Experimental set-up. A-helical antenna; T-glass tube; C-collector; P-plane Langmuir probe; RF - radio-frequency power supply; MC - matching circuit.

minimum at $z = 0$, followed by a maximum at about $z = 1$ cm. The peak of the electron temperature in this transition region is $\Delta T_e \approx 3$ eV.

The axial profile of the electron concentration, plotted in Fig. 4, shows that going downstream, the electron concentration has a global increasing tendency. Anyway, at $z = 1$ cm, the electron concentration profile displays a small bump.

3. Analysis of experimental results

The experimental results emphasize that the plasma electrons produced upstream are accelerated towards the main chamber of the experimental device (Fig. 2) by a relatively strong axial electric field. In this way, on a short distance (between $z = -11$ cm and $z = -2$ cm), the electrons could, in principle, gain sufficient energy for ionizing the neutrals, but in the same region the electron temperature is decreasing (Fig. 3), due to inelastic collisions with the neutrals. This means that the sudden decrease of the space potential and of the electron temperature at $z = 0$ is the result of neutral excitation by electron collisions. Consequently, the electrons exciting the neutrals gather there and form a net negative space charge, explaining in this way the existence of the two local minima (for Vs and Te) at $z = 0$.

The electrons that have not excited the neutrals are further accelerated by the electric field and, after traveling about 1 cm downstream, rich enough kinetic energy to ionize the neutrals. This explains the sudden increase of the electron temperature at $z = 1$ cm, as well as that of the plasma potential in the same place. The electrons that ionize the neutrals and those resulting from this process are transported downstream by diffusion. From Fig. 2 it can be seen that downstream the electric field is approximately zero, hence a drift movement of the electrons downstream is excluded.

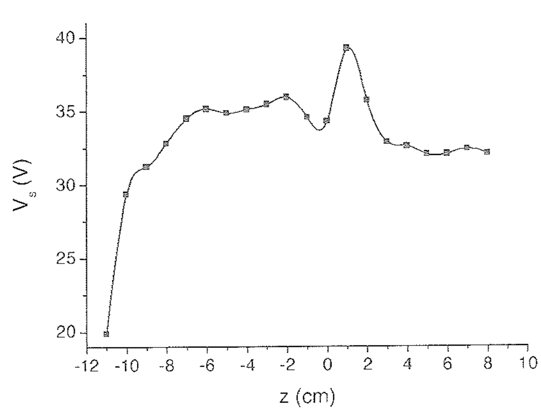

Fig. 2 Axial profile of plasma potential.

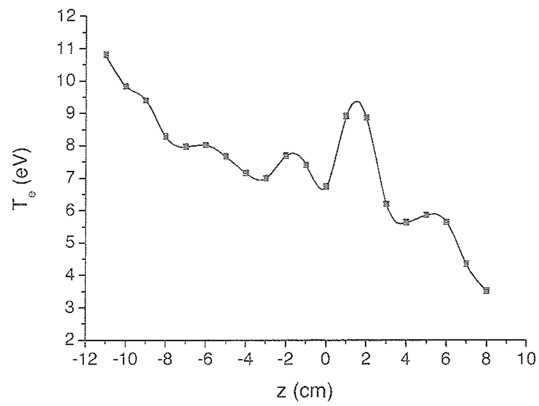

Fig. 3 Axial profile of electron temperature.

The positive ions resulting after neutral ionization form a net positive space charge, adjacent to the net negative one. The electrostatic forces of attraction between these two opposite layers, acting as long-range correlations, "bind" them together in the form of an electric double layer [3]. The appearance of this double layer in the absence of an externally imposed conduction current, makes it current-free, in accord with the earlier experimental reports [1,2]. Taking into account that, for the above working conditions the Debye length is $\lambda_D = 0.3$ mm and the double layer thickness is $\Delta z_{DL} = 1$ cm, we can conclude that this potential structure is narrow. Also, comparing the potential drop on the double layer with the electron temperature downstream, expressed in eV, one obtains the strength of the double layer $\eta_{DL} = \Delta V_{DL}/T_{e,\,eV} \approx 1$, meaning that this potential structure is a weak one.

The fact that the upstream, respectively downstream plasmas are different is also proved by the "Maxwelliazation" coefficient α calculated in different points along the axial direction of the device (Fig. 5). This coefficient measures the number of orders of magnitude of the electronic current over which the semi-log plot $\ln I_e(V)$ is linear (V being the variable probe potential), ensuring in this way the degree of accuracy in the calculation of the electron temperature. From Fig. 5 it can be seen that upstream the linearity domain of the electronic current on the semi-log plot is ensured for less than one order of magnitude for I_e, while downstream the linearity domain is wider. This proves that downstream the energy distribution function for electrons is much closer to the Maxwellian one than upstream, or, with other words, that the plasma is more turbulent upstream than downstream.

4. Conclusions

The above experimental results prove that a current-free electric double layer can also appear in magnetized inductively coupled plasmas at moderate pressures, *i.e.* above 1 mTorr, but unlike the small pressure case [1,2], it is a

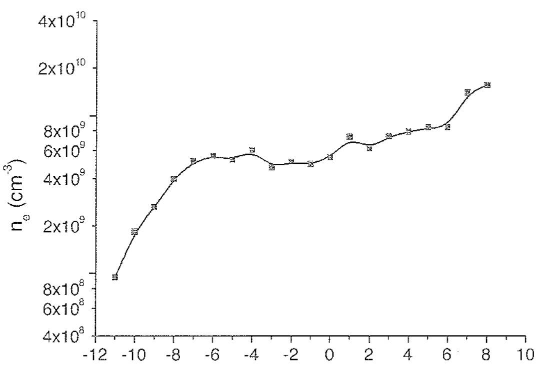

Fig. 4 Axial profile of electron concentration.

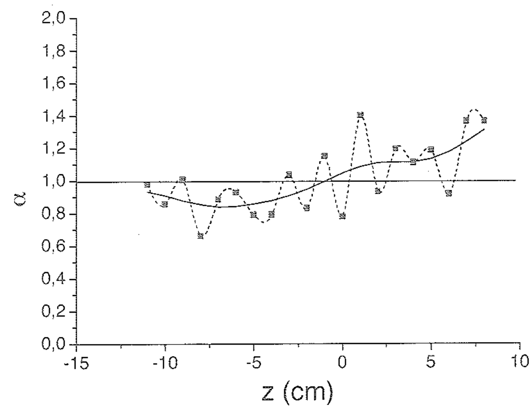

Fig. 5 Degree of Maxwelliazation of energy electron distribution as a function of axial position. The full curve is the smoothed version of the dashed one.

weak one. This narrow and weak double layer is the result of a self-organization process taking place inside the plasma column, *i.e.* it appears as the result of the intrinsic dynamics of the plasma particles, and not the consequence of an external constraint [3]. The double layer self-assembles during the plasma breakdown [2] and remains in a steady state afterwards. It acts as an internally built boundary between two plasma regions with different properties: one with high electron temperature and small electron concentration (upstream) and one with high electron concentration and small electron temperature (downstream).

References

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