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PLASMA BUBBLES ON LANGMUIR PROBE IN AN INDUCTIVELY COUPLED PLASMA

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Abstract. Plasma bubbles have been observed experimentally on Langmuir probes in an inductively coupled plasma created by a helical coil around the plasma source. The bubbles are due to two double layers which prove to be the saturation stage of the Buneman instability. Simultaneously with the bubbles appearance there is an increase of the probe current which is accompanied by a drop of the plasma resistance. A typical hysteresis dynamics for double layers have been observed.

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Radio frequency created plasmas are very promising for applications targets. Capacitively coupled plasmas are relatively well investigated (see e. g. [1]). Recently inductively coupled plasmas (ICPs) have found an increasing interest due to their possible use for implantation [2] and etching devices [3]. These plasmas are very promising for plasma source ion-implantation [4]. There is a progress both in theory and experiments of ICPs, created by a plane-spiral coil [5, 6]. However there are only a few experiments (see for example [7] with helical coil among which is the Frankfurt PIII-experiment (Plasma Immersion Ion Implantation — Fig. 1).

Doing plasma measurements we have encountered light bubbles at high current probe regime (Fig. 2). The measurements are conducted with argon, oxigen and air (only the one with argon is presented). There has been no evidence of an influence of the plasma bubbles to the volume plasma.

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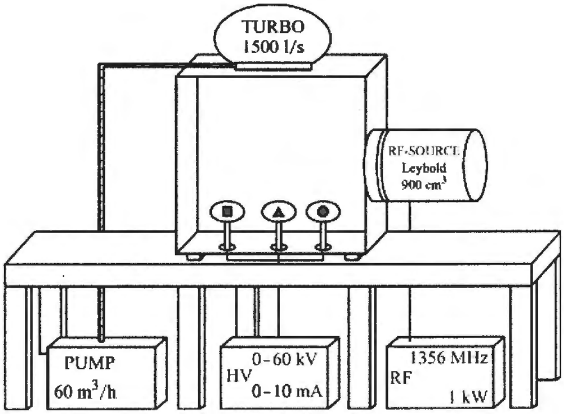

Fig. 1. Scheme of the PIII experiment at Frankfurt University. A Leybold ion RF source is mounted to the target chamber and coupled to a 13.56 MHz RF generator (details of the source are presented in [2]). During plasma measurement the targets are put away

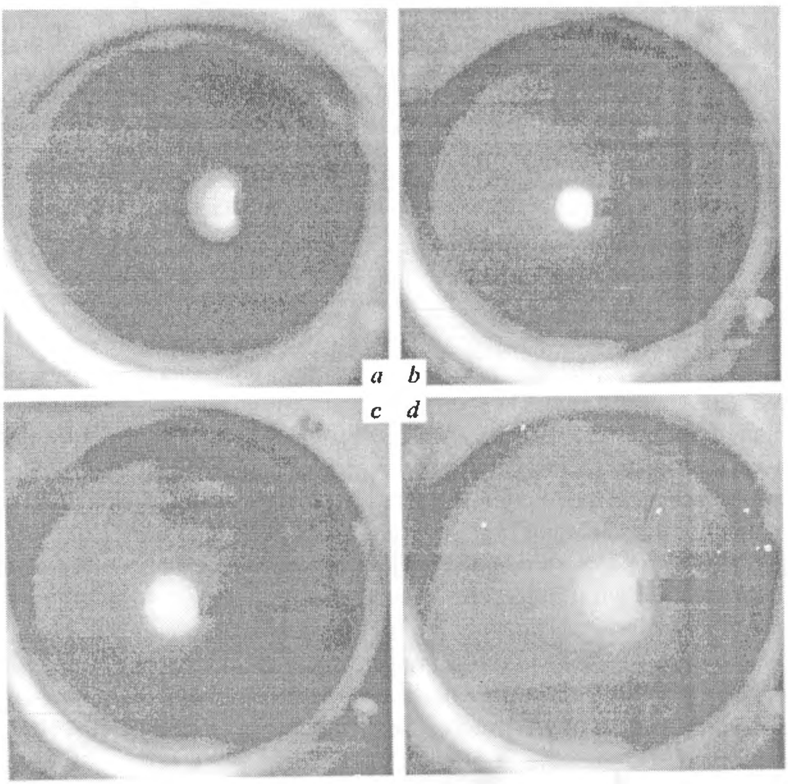

Fig. 2. Different bubbles at $x = 20$ cm, $U = 100$ V, $P = 10$ W
(*a*) bubbles at very high pressure $p = 7.3\times10^{-2}$ mbar; (*b*) small bubbles at $p = 1.8\times10^{-3}$ mbar; (*c*) big bubbles at $p = 4.3\times10^{-4}$ mbar; (*d*) bubbles with halo at $p = 6\times10^{-4}$ mbar

These bubbles appear due to double layers (DLs). A qualitative description of the general phenomena of DLs in direct current discharge and in plasmotron ones are given [8]. We would like to mention the two reviews [9, 10], where the problem is treated in detail in DC multi-plasma devices as well as in plasmotrons. We shall comment only DC devices. DLs appear in thermionic emission devices or in such "where a potential is applied between independently generated discharges which are separated by grids" [7]. In our experiments there is neither thermionic emission nor grids. The plasma in the chamber could be concern as "independently created", because it is created by the RF field. Thus our experiment can be considered conditionally as a double plasma device [9].

The bubbles appear at high voltage and/or pressure, that is at a high ionization rate with quite a big increase of the probe current. Without positive probe voltage it is not possible to observe them. They appear only when there is a drift of electrons relatively to ions. The bubbles are in fact saturation of Buneman's instability with a large growth rate. When the growth rate is small, we can observe DLs as weak and small auroral bubbles (lightly blue ones).

Qualitatively this phenomenon is explained in Fig. 3. The plasma particles form two DLs, closed to the probe. The potential U_+ of the "hill" is higher than the probe potential. For this reason there are two kinds of particles — trapped and accelerated. The plasma electrons out of the "hill" space are accelerated by the first DL so they can overcome the potential "hill-probe". Ions from the "hill" space are accelerated in the opposite direction. Plasma ions and "hill" electrons (slow ones) are repelled from the first (left) DL, that is they are trapped particles. The bubbles current jumps because it consists of the electron current and that of the repelling ions.

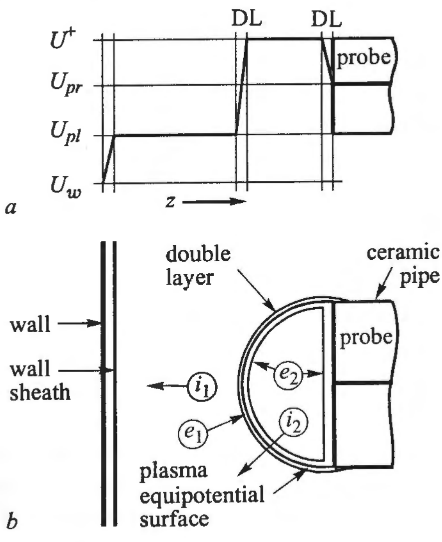

Fig. 3. Qualitative drawing of the potential distribution (*a*) and double layer on the probe in ICP (*b*)
The Langmuir probe consists of a copper disc with a diameter of 12 mm and a thickness of 1 mm, which is connected to the voltage feed through at the plasma chamber by means of a stainless steel rod, which is shielded by a ceramic pipe

When the pressure is decreasing the bubbles change — at a high pressure we have bubbles similar to a hemisphere with relatively low brightness (Fig. 2*a*) and with a clearly expressed blue halo. With increasing the vacuum the bubbles change to a small (Fig. 2*b*) and a big (Fig. 2*c*) bright white balls. Then the bubble size increases and an yellowish halo appears around the ball (Fig. 2*d*). At certain current and pressure the bubble disappears (Figs 4 and 5).

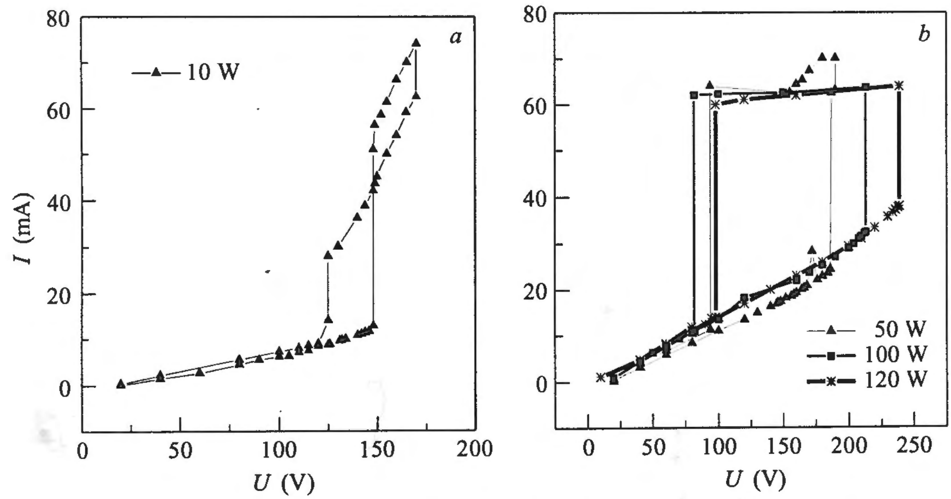

Fig. 4. The dependence of the probe current on the voltage, $I = I(U)$, at different RF powers

The experimental curves are presented in Figs 4 and 5. In Fig. 4 we can see the dependence of the probe current on the voltage at different RF energies. (The distance x is taken from the opposite of the ion source wall.) We should note that this is the RF source energy. We did not conduct the investigation how the energy is going into plasma. The hysteresis character of this dependence is demonstrated. At the appearance of the bubble the plasma resistance becomes so small that our supply allows only to achieve the voltage of the bubble, but not to increase it (or to increase it unessentially). The voltage extension, however is possible at a 10 W RF power (Fig. 4*a*). The double loop character of the hysteresis current-voltage dependence, when the supply is sufficiently strong, is typical for the probe plasma bubbles. The hysteresis is typical phenomenon of DLs [9]. One can see also the hysteresis character of the dependence of the current on the pressure at $U = \text{const}$. In Fig. 5 the current-pressure dependence is shown.

The question of inductive and capacitive coupling of the coil arise. From Fig. 4 one can see that it is easier to obtain a bubble at low RF powers. For ICP with a plane coil this problem is discussed in a very interesting article [11]. It is proved experimentally there that at low RF energies the capacity coupling of the coil with the plasma dominates. On the contrary, at high RF power the inductive coupling dominates. We doubt in such a possibility in our experiment. The final rejection of the idea for a device, employing helical coils around it, can be done after doing experiments with a special screen of the coil electric-field, similar to that in [11].

There are three facts which support the RF field stabilisation of the discharge. First, with decreasing the distance between the probe and the RF source, hence with increasing RF field, the appearance of the bubbles becomes more difficult at a higher current and a higher pressure (Fig. 5). The increasing current, which is necessary for the bubbles' appearance, dependent on the RF power is seen in Figs 4 and 5. Second, the bubbles' regime close to the source wall, is impossible. Third, the bubbles inside the ion source were not observed at any probe voltage. But this is a seeming reason. A careful analysis shows that in all these cases the stabilisation of the discharge correlates with the increasing plasma density. This is seen in Fig. 6. One can suspect [8] that the main reason is the ionisation rate. For final response of this problem additional experiments are necessary.

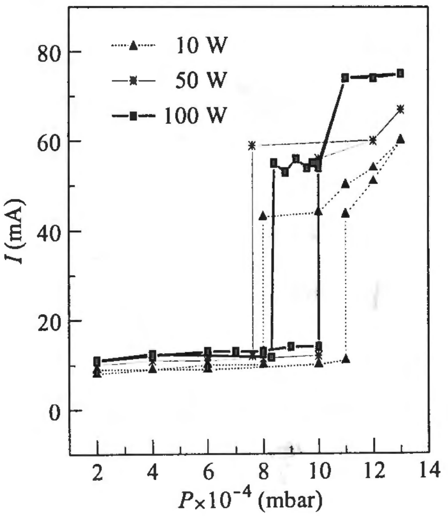

Fig. 5. The dependence of the probe current on the chamber pressure, $I = I(p)$, at different powers ($p = 4 \times 10^{-4}$ mbar)

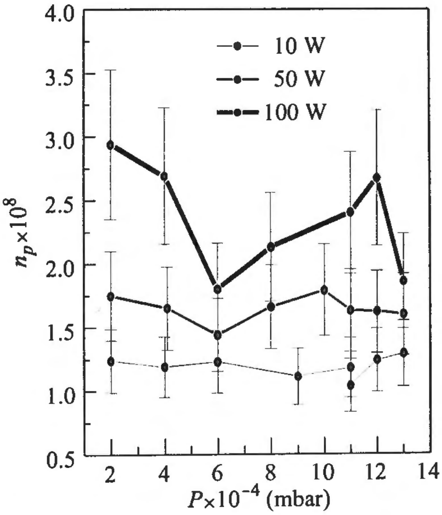

Fig. 6. The increasing of the plasma density with RF power ($U = 120$ V)

We would like to discuss two criteria for DLs [8]. The first, which was delivered by Langmuir [12], states that the ratio of the ion and electron-current densities must be equal to the root of their mass ratio:

$$j_i/j_e = \sqrt{m_i/m_e}\,. \tag{1}$$

For argon this gives $j_i/j_e = 2.7 \times 10^{-2}$, for oxygen 1.7×10^{-2}, and for nitrogen 1.6×10^{-2}. As one can see electron-current density j_e in various gases is almost the same; these data should be considered as relatively ones for the current at which bubbles appear. Really in our experiment the bubbles appear in air at lowest current, in oxygen — at a higher current and in argon — at the highest one, $j_{\rm ar} : j_{\rm air} : j_{ox} = 6.3 : 4 : 3.7$. For an estimation we have taken atomic nitrogen and oxygen, according to the last spectroscopic measurement in plasma, created by a helical coil around it [13]. At the end we would like to note that for different working gases the bubbles change not only their colour, but also their form.

The second criterion which was derived by Bohm for plasma wall sheats [14] applies to strong DLs [9]. It requires the current density through the sheath to be greater than the critical density j_c, which depends on the electron temperature and plasma density.

A comparison of the critical current density

$$j_c = n_e e \sqrt{2kT_e/m_e} \tag{2}$$

and the experimental data shows drastic disagreements. For example at $x = 1$ cm, $P = 10$ W and $p = 4 \times 10^{-4}$ mbar the theory yields $j_c = 8.75$ A/m^2 , while the experiment measurements give 0.045 A/m^2! This demonstrates that the bubbles in our inductively coupled plasma are not strong. They are essentially different than those investigated in accelerators and multi-plasma machines (see [8], where the pressure is of the order of 1 Torr and the bubbles current is of the order of a few Amperes).

At the end we summarise the observed results. At sufficient high voltage and pressure we observe different kind of bubbles. In each cases the critical current through the system is important. The phenomenon is easily observed at a low RF energy. At equal conditions with increasing the distance from ion source it becomes easier to obtain bubbles. They follow the equipotential surface. Closed to the down chamber wall the bubbles are flattened. The bubbles are the result of two DLs near the probe which represent a final saturated stage of the Buneman instability. The typical hysteresis phenomena both for current-voltage and for current-pressure dependences have been observed. The increasing of the RF field stabilizes the discharge through the growing plasma density. At the bubbles appearance the plasma resistance becomes very small (on our rough estimation it is approximately 1-1.5 kΩ). Therefore a detailed analysis of plasma bubble phenomenon is necessary and experiments with an additional fine probe, by which one can penetrate in the bubbles and measure their characteristics [15] should be carried out.

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