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Sputtering effects in a helicon plasma with an additional immersed antenna

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Abstract
A plasma source excited by a double saddle helicon antenna outside the glass vacuum vessel has been modified by inserting a second copper antenna in contact with the plasma through the glass end plate. Both have the same frequency of 13.56 MHz but have a different phase. The immersed antenna is electrically floating, allowing a negative self-bias to form, leading to ion bombardment and sputtering of the copper onto the inner walls of the source tube. Dramatic changes in all plasma parameters (plasma density and potential, electron temperature, self-bias) are measured as the copper film increases in thickness, effectively shielding the power coupling of the helicon antenna. For low helicon powers the density decreases with time, but for high powers a copper free path is left in the glass adjacent to the helicon antenna due to re-sputtering of the deposited copper and no change in the plasma density is observed. This opens the possibility of having a 'negative' helicon antenna made of a copper cylinder with the antenna being the 'cut out' portion, opposite to the normal construction of helicon systems.

1. Introduction

In coupling radio frequency (RF) power in the megahertz range to plasmas two basic systems have been employed, one with the antenna immersed in the plasma and in direct contact with the charged particles, and the other with the antenna outside the vacuum vessel containing the plasma. The non-capacitive power transfer, where a dielectric barrier is used to shield the RF antenna from the plasma has shown to be more efficient over the one using electrodes directly exposed to the plasma [1]. Typically, low voltages across the plasma sheaths are achieved and the impurities from directly exposed electrodes are avoided. Nevertheless, many plasma processes require the thin film to be bombarded by energetic particles to help in breaking the bonds of the material in the case of etching, and in compacting a growing film in plasma deposition. This problem is normally solved by adding an electrode to mimic the effect of the capacitively coupled systems, but with the advantage of the higher ion density and the almost completely independent control of the ion current and energy impinging on the substrate. Fully immersed antennae have also been used in plasma immersion ion implantation to improve the 'inductive' coupling of the antenna to the plasma and to enable the plasma to be generated in an enclosed metallic vacuum chamber. The plasma potential and the antenna self-bias, when it was floating electrically, led to considerable sputtering of the antenna [2]. Sugai *et al* [3] describe experiments on external and immersed antennae and the generation of large self-biases on the materials surrounding the antennae leading to the release of impurities. For years there have been problems with impurities and undesirable deposited coatings in the reactor which change experimental conditions and led to irreproducibility. However, experimentalists have learned to deal with these problems and there have been few reported measurements of these phenomena.

In this paper a small copper antenna was introduced into a traditional helicon source, having the same frequency as the main helicon antenna. The small antenna was directly exposed to the plasma and isolated from ground so that a self-bias was formed, giving rise to severe sputtering of the antenna material.

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2. Experimental set-up

The horizontal helicon system used for the experiments reported here has been described previously [4, 5]. The experiments were carried out with argon at a pressure of 4 mTorr, and a decreasing magnetic field from the source to the diffusion chamber, with a maximum magnetic field of ∼100 G in the source. A three-dimensional sketch of the antennae system is shown in figure 1. The plasma is excited mainly by a 20 cm long double saddle type helicon antenna (H-antenna), one end of which is earthed. RF power at 13.56 MHz is fed to this antenna via a L-matching network, and the forward and reflected powers are monitored through a standing wave ratio meter (SWR). An additional 6 cm long bare copper antenna is immersed 8 cm into the plasma through the aluminium-end-plate of the source. The small antenna (S-antenna) is also fed with RF power at 13.56 MHz via a separate π-matching network, and the forward and reflected power are also monitored through a SWR. The power on the H- and S-antenna will be referred to as H-power and S-power, respectively. The phase difference between the two antennae can be separately controlled. For all experiments described here the phase difference was kept constant. In addition to the π-matching network the S-antenna is DC isolated by a 10 nF capacitor placed between the generator and the matching box allowing a negative DC self-bias, V_{sb}, to form on the antenna. The latter is measured by using a low pass filter connected to the S-antenna.

A Langmuir probe (LP) is introduced via the aluminium end plate of the diffusion chamber, and is 1 cm away from the S-antenna in the horizontal plane of the antenna. The Langmuir characteristics are obtained using a Labview acquisition system, where the probe voltage, V_{pr}, is swept from +40 to −30 V with an increment of 0.7 V (100 steps), and the voltage is kept at −30 V between the sweeps. RF plasma potential fluctuations can alter the current–voltage characteristics measured by a LP, but in our case the second derivative of the characteristic has typically a maximum and minimum separated by less than $2kT_e$, and the amplitude of the floating potential fluctuation is less than kT_e, which indicates that the LP measurements are not effected by RF [6]. Analysis of the LP characteristics as described in [7] gives the plasma (V_p) and floating potentials (V_f), the electron temperature (T_e) and the plasma density (n_i).

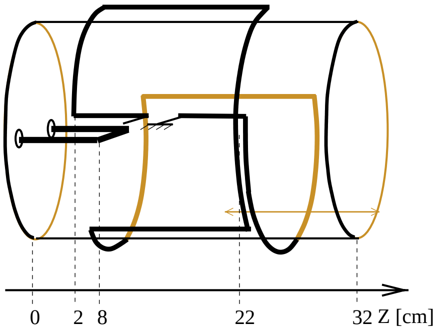

Figure 1. A three-dimensional sketch of the antennae system, showing the double saddle type helicon antenna outside the cylindrical quartz tube, and the second copper antenna (S-antenna) immersed into the quartz tube through an aluminium end plate. The arrow indicates where the measurements in figure 5 were taken.

3. Results and discussion

The plasma parameters, n_i, T_e, V_p and the self-bias on the small antenna, V_{sb}, were measured as a function of the power on the H-antenna (up to 1 kW) with a constant S-power of 20 W. The results are shown in figures 2 and 3 for three source wall conditions: a clean source wall (no copper coating), a thin copper coating and a thick copper coating on the source wall, respectively. The copper coating on the source walls results from the sputtering of the S-antenna in contact with the plasma. Initial results with a clean tube (solid circles) show that n_i increases monotonically with the H-power, T_e changes very little (∼3.5 eV) and $|V_{sb}|$ decreases as n_i increases, which is to be expected from power balance conservation. Results obtained with a thin copper coating on the source wall (diamonds) were somewhat different: the increase in n_i is less dramatic, and the evolution of T_e, $|V_{sb}|$ and V_p has changed. For a thick copper coating (triangles) the changes were even more dramatic and the density was lower by a factor of 2–10 over the H-power range compared to the initial experiments in a clean tube. T_e changed once again and $|V_{sb}|$ increased.

Figure 2(*a*) shows that the density monotonically increases with the H-power for the three wall conditions. However, for a coated tube there is a density jump occurring at $\sim 5.5\times10^{10}\,\mathrm{cm}^{-3}$ for power values between 300 W and 400 W and 600 W and 700 W for a thin and a thick copper layer,

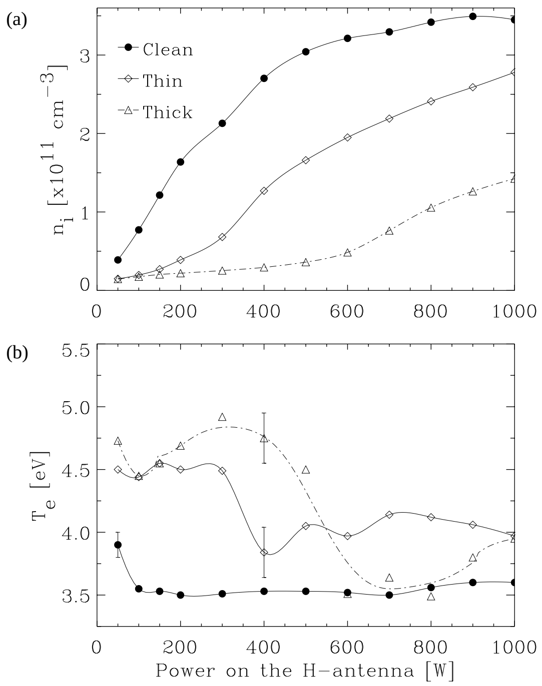

Figure 2. (*a*) Plasma density, n_i, and (*b*) electron temperature, T_e, as a function of H-power, with a constant S-power of 20 W and a constant Ar pressure of 4 mTorr. Closed circles are results obtained in a clean quartz tube, while open diamonds and triangles are obtained in a tube coated with a thin and a thick layer of copper, respectively.

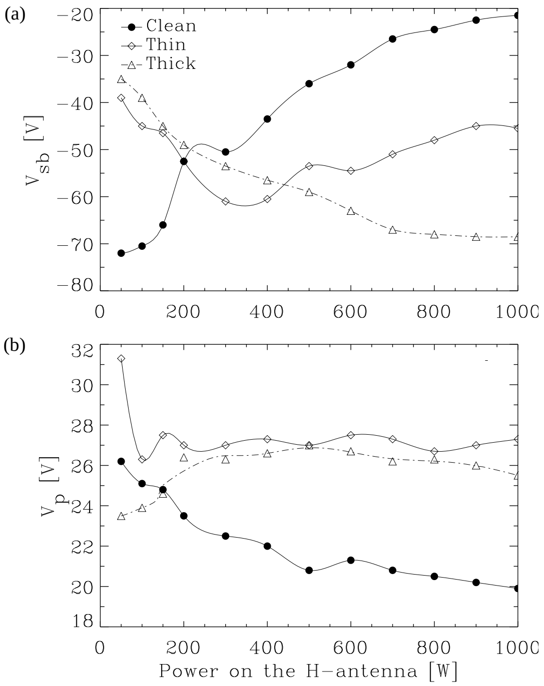

Figure 3. (*a*) Self-bias, V_{sb}, on the small antenna, and (*b*) plasma potential, V_p, as a function of H-power; same operating conditions as figure 2.

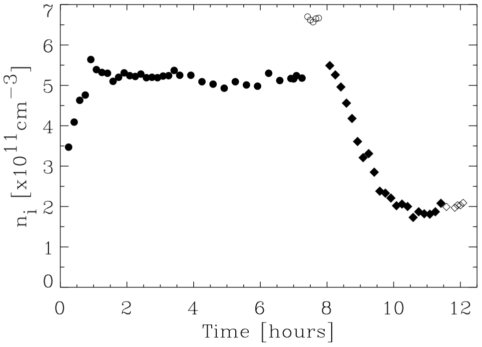

Figure 4. Plasma density as a function of time, with varying powers as follows: from 0 to 7.3 h (●): H-power = 300 W, S-power = 20 W; from 7.3 to 8 h (○): H-power = 250 W, S-power = 70 W; from 8 to 11.5 h (◆): H-power = 150 W, S-power = 70 W; and from 11.5 to 12.2 h (◇); H-power gradually changed from 150 to 0 W and S-power = 70 W.

respectively. The electron temperature, figure 2(*b*), is constant for a clean tube, except for the first measurement at 50 W. In the case of a thin coating T_e is high (4.5 eV) at low powers, suddenly decreasing to a lower temperature (4.0 eV) at 300–400 W. For a thick coating T_e has a similar behaviour with a more pronounced jump occurring at 600–700 W. As previously reported by many authors [8,9], a capacitive to inductive mode transition occurs with a density jump to higher values, usually at a threshold of $\sim 5.5 \times 10^{10}$ cm^{-3}, and associated with a sudden decrease in T_e. For all wall conditions we measure a high T_e of ~4.5 eV when the measured density is lower than the threshold of $\sim 5.5 \times 10^{10}$ cm^{-3}. Hence, our results indicate that the plasma is in an inductive or helicon mode throughout the whole H-power ramp for a clean tube, and when the tube becomes coated, the density threshold appears at higher H-powers as the thickness of copper deposition increases. The copper deposited on the source wall probably acts as a Faraday shield for the helicon antenna [3, 10], suppressing some or all the H-power coupled from the antenna to the plasma.

A controlled set of experiments, starting with a clean tube, were carried out over a period of 12 h (figure 4). For the first 7.3 h the H-power was 300 W and the S-power 20 W (closed circles), i.e. a total power of 320 W. The density increased from 3.5×10^{11} to 5.5×10^{11} cm^{-3} between 0 and 1 h, and subsequently stayed constant for 6 h ($t = 7$ h). The initial density increase was due to outbaking of residual cleaning products (a stainless steel pickling gel (weld cleaner) with 300 g l^{-1} nitric acid and 50 g l^{-1} hydrofluoric acid) used for removing the copper coating deposited in the previous experiment. After the first 7.3 h there was no obvious change in plasma density and the H- and S-powers were changed to 250 W and 70 W, respectively (open circles), in order to increase the sputter rate by increasing the self-bias from −50 to −100 V, but keeping a total power input of 320 W. Under this condition the density increased by about 20%, surprisingly showing a better efficiency of the S-antenna compared to that of the helicon antenna in this case. However, no change in the plasma density was observed with time. Therefore, at 8 h, the powers were changed to 150 W on the helicon while keeping 70 W on the S-antenna (closed diamonds), hence lowering the total power input to 220 W. The density decreased by 70% between 8 and 9.5 h, and remained constant thereafter. From 11.6 to 12.1 h, the S-power was maintained at 70 W while the H-power was changed every 5 min from 70 to 50, 20, 10 and 0 W (open diamonds). The constant density measured in the last phase showed that the helicon antenna was totally shielded for H-powers <150 W ($t = 10$ h).

The copper film deposited on the source tube during these experiments was clearly nonuniform. During the first 7 h, when no change in the plasma occurred, careful observations showed that a small amount of copper was deposited on the wall, but a copper-free path was left on the glass along the H-antenna. After 12 h the same pattern was observed, but with a thin copper layer on the glass adjacent to the H-antenna and a thick copper on the part of the tube not affected by the presence of the H-antenna. The resistance of the copper layer was measured at various points and showed a high resistance for thin copper coating and a low resistance for thick coating, in agreement with the visual observations. This non-uniformity in the copper deposition suggests that there exists a more negative potential bias on the glass wall adjacent to the H-antenna [11, 12], and that the copper deposited on the walls might be resputtered near the H-antenna.

To investigate this issue a third series of experiments was performed by measuring the potential V_w on the clean source wall [13, 14] adjacent to the H-antenna, with the S-antenna removed from the plasma. With the LP in direct contact with the wall, the first 'static' method consisted of connecting the LP directly to a high impedance (1 MΩ) oscilloscope. The second 'dynamic' method consisted of adjusting the bias on the LP to obtain a zero current on the probe.

The results shown in figure 5 were obtained for two H-power conditions of 300 W (diamonds) and 150 W

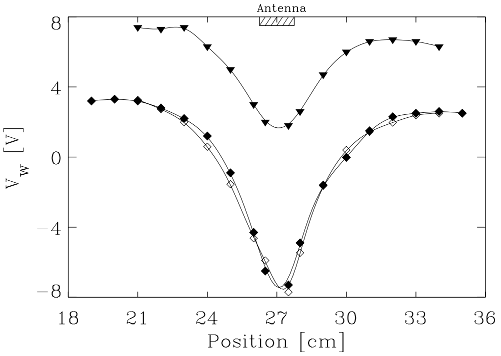

Figure 5. The wall potential, V_w, as a function of axial distance along the source passing a section of the helicon antenna as shown by the arrow in figure 1. The size and position of the antenna strap is drawn. Open and closed diamonds are obtained with 300 W H-power, while closed triangles are with 150 W H-power.

(triangles), over an axial distance of 16 cm along the source wall intercepting the H-antenna as indicated by the arrow in figure 1. A 4–6 cm wide negative biased well adjacent to the H-antenna is observed for both powers, although less pronounced when the H-power is reduced to 150 W. The width of the measured potential well agrees with the visual copper free path previously observed and with sheath width modelling [12]. With 300 W H-power a minimum potential of −8 V is measured on the glass wall next to the H-antenna and a constant value of about +3 V is measured on the unaffected part of the wall. Sugai *et al* [3] reports on negative self-biases of ∼−20 V measured on a 1.2 cm thick insulation between an inductively coupled RF antenna powered by 300 W and the plasma. Enhanced window erosion in ICP reactors, caused by large negative voltages on the window close to the inductive antenna, has also been reported [9].

Since the RF voltage varies along the H-antenna, the negative bias voltage measured at the wall is dependent on the distance along the H-antenna, the quality factor of the circuit and the thickness of the insulation [3]. The ion acceleration to the wall adjacent to the H-antenna is dependent on the plasma parameters and on the antenna voltage [12] and will induce a non-uniform resputtering of deposited copper along the glass near the antenna. With sufficiently large H-powers a copper free path will be left adjacent to the H-antenna, while as for lower H-powers the resputter rate decreases, allowing for a copper coating along the H-antenna as well as on the remaining undriven part of the tube, hence creating a Faraday shield. Additional experiments showed that even with large H-powers, an initial clean tube is necessary for maintaining a copper-free path.

4. Summary and conclusion

A traditional helicon source was modified by introducing a second copper antenna into the plasma. While the helicon antenna was separated from the plasma by a pyrex tube, the second antenna was immersed and directly exposed to the plasma. The small antenna was DC isolated from ground, so that a negative self-bias formed on the antenna and gave rise to significant sputtering of the antenna material (copper). Dramatic changes in all plasma parameters (plasma density and potentials, electron temperature and self-bias on the S-antenna) where measured as copper was deposited on the source walls. The plasma parameters were measured as a function of H-power for three different source wall conditions, i.e. clean wall, thin and thick copper coating. The capacitive to inductive transition occurred at higher H-power thresholds when the coating increased in thickness and acted as a Faraday shield for the H-antenna. Monitoring the plasma density over a period of 12 h for varying powers on the H- and S-antenna revealed the absence of the Faraday shield for high H-powers (>150 W): starting with a clean tube, a copper-free path was left on the glass following the geometry of the helicon antenna at high H-powers, while as for lower H-powers this area was gradually covered by copper. The copper-free path was correlated to the measurement of a negative potential bias on the wall adjacent to the helicon antenna, inducing resputtering of the deposited copper material and allowing the antenna to function normally. This opens the possibility of having a ‘negative’ helicon antenna made of a copper cylinder with the antenna being the ‘cut out’ portion, opposite to the normal construction of helicon systems.

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