On the influence of a single probe on the spatial distribution of the plasma parameters in a small-radius inductively-driven discharge in hydrogen

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A 2D fluid model of a low gas-pressure hydrogen discharge is employed for studying the influence of a single Langmiur probe on the spatial distribution of the plasma parameter in a small-radius discharge. The results presented are for the 2D spatial distribution of the plasma parameters (electron density and temperature and plasma potential) without a probe and for the relative deviations in their distribution introduced by the probe. The latter are obtained for different values of the bias applied to the probe tip. In the discussions, the influence of the probe bias is marked off from that of the probe holder. The analysis of the results shows that: (i) the probe affects the plasma parameters beyond the region of the plasma sheath, (ii) the pattern of the deviations of the plasma parameters slightly shifts towards the probe when the bias applied to its tip increases, and (iii) changes in the gas pressure lead to modifications of the spatial region of influence of the probe on the plasma parameters.

1. Introduction

The ion plasma sources have a wide range of applications, which are of importance not only for the industry and the medicine, but also for the neutral-beam-injection plasma heating systems in big fusion machines like ITER and DEMO. Whereas the operation of the source for ITER [1] is based on surface production of the negative ions, with caesium, the direction toward DEMO is for a non-caesiated source. The latter stimulates the studies on Cs-free sources of negative hydrogen ions like the matrix source [2]: a matrix of small-radius discharges inductively driven by a planar coil. The concept is based on the nonlocality governing the behaviour of the low-pressure discharges which results into strong accumulation of volume-produced negative hydrogen ions in the region of the maximum of the plasma potential [2-4]. Recent experiments on probe diagnostics [5,6] and on the extraction [7] carried out in a single element of the source show that the control on the spatial distribution of the plasma potential, being a key point in the source design, should be based on reliable diagnostics. A single Langmuir probe, positioned on the discharge axis, and movable in the axial direction, is used in the experiments for obtaining the axial variation of the plasma parameters. However, such an arrangement of the probe could influence the plasma parameters. This study aims at analyzing such an issue by applying a 2D fluid plasma model.

2. Formulation of the problem

The modelling domain, presented schematically in Fig. 1, is in the (r–z)-plane. Its size corresponds to that of the discharge tube used in the experiments [5,6]: the radius is 2.5 cm and the tube length is 12 cm. The probe is positioned along the z-axis at 3 cm away from the left bottom of the tube where the planar coil is located. The probe tip is with a radius of 0.3 mm and a length of 6 mm. The radius of the dielectric holder of the probe is also 0.3 mm. A super-Gaussian profile of the power deposition P_{ext} is assumed (Fig. 1) for reproducing the planar coil inductive driving of the discharge.

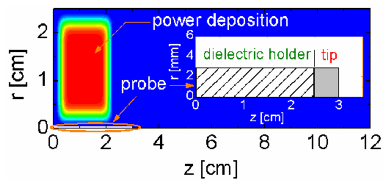

Figure 1. Illustration of the modelling domain with the configuration of the probe. The rf power deposition region is also given.

The model (a 2D model) is within the fluid plasma theory for a hydrogen discharge in a free-fall regime. The charged particles are electrons (α = e) and the three types of positive ions ($\alpha \equiv j = 1, 2, 3$ for H^+, H_2^+ and H_3^+ ions). The free-fall regime of the discharge is specified via effective mobilities which account for the inertia term in the momentum equations of the ions [8]. The initial set of equations includes the continuity equations for the charged particles and for the hydrogen atoms, the electron energy balance equation and the Poisson equation:

$$\mathrm{div}\,\boldsymbol{\Gamma}_{\alpha} = \frac{\delta n_{\alpha}}{\delta t}, \qquad (1)$$

$$\mathrm{div}\,(-D_{\mathrm{a}}\nabla N_{\mathrm{a}}) = \frac{\delta N_{\mathrm{a}}}{\delta t}, \qquad (2)$$

$$\mathrm{div}\,\mathbf{J}_{\mathrm{e}} = P_{\mathrm{ext}} + P_{\mathrm{coll}}, \qquad (3)$$

$$\Delta\Phi = -\frac{e}{\varepsilon_0}\left(\sum_{j=1}^{3} n_j - n_{\mathrm{e}}\right). \qquad (4)$$

The density of the hydrogen molecules is obtained from the equation of state $p = \kappa T_{\mathrm{g}}(N_{\mathrm{a}}+N_{\mathrm{m}})$, where κ is the Boltzmann constant and T_{g} is the gas temperature (taken with a value of 300 K); N_{a} and N_{m} are, respectively, the densities of the hydrogen atoms and molecules. In (1-4), n_{α} are the densities of the different types of charged particles and $\boldsymbol{\Gamma}_{\alpha}$ are their fluxes, D_{a} is the diffusion coefficient of the atoms, $\mathbf{J}_{\mathrm{e}}$ is the electron energy flux, and Φ is the plasma potential ($\mathbf{E}_{\mathrm{dc}} = -\mathrm{grad}\,\Phi$); e and ε_0 are, respectively, the elementary charge and the vacuum permittivity. The particle production and losses (the right-hand side of (1) and (2)) and the electron energy losses in collisions P_{coll} (in (3)) are, as described in [9].

The boundary conditions are for symmetry at $r = 0$, and for the charged-particle and electron energy fluxes at the walls, as given in [10]. The boundary conditions for the Poisson equation (4) are for metal walls of the discharge vessel and a dielectric surface of the probe holder as well as for the bias U_{pr} applied to the probe tip. The boundary condition for the atoms accounts for their wall recombination.

Conclusions about the influence of the probe (through the bias applied to it and as a body immersed into the plasma) on the spatial distribution of the plasma parameters are aimed at. Consequently, the results obtained with a probe are compared with those without a probe using the quantity

$$\frac{\Delta\Theta_k}{\Theta_k} = \frac{(\Theta_k)_{\text{with probe}} - (\Theta_k)_{\text{w/o probe}}}{(\Theta_k)_{\text{w/o probe}}}, \qquad (5)$$

where $\Theta_k = \{n_{\mathrm{e}}, T_{\mathrm{e}}, \Phi\}$, as a relative deviation in the spatial distribution of the plasma parameters. Positive $\Delta\Theta_k/\Theta_k$ means that with a probe the local value is higher than that without a probe, and vice versa. In the obtained results a value of $|\Delta\Theta_k/\Theta_k| = 10\%$ is assumed as a reference point for determining the regions of influence of the probe on the plasma parameters. The influence of the holder of the probe (i.e., the probe as a body) and of the bias applied to its tip are separated via comparing the results for $\Delta\Theta_k/\Theta_k$ obtained at a bias U_{pr} corresponding, respectively, to the floating potential ($U_{\mathrm{pr}} = U_{\mathrm{fl}}$), and to the regions of the ion- and electron-saturation currents in the I-V probe characteristic.

3. Results

The results presented are obtained at $P_{\mathrm{ext}} = 50$ W, for two values of the gas pressure ($p = 10$ mTorr and 50 mTorr) and three values of the bias applied to the probe tip ($U_{\mathrm{pr}} = -80$ V, $U_{\mathrm{pr}} = U_{\mathrm{fl}}$ and $U_{\mathrm{pr}} > \Phi$).

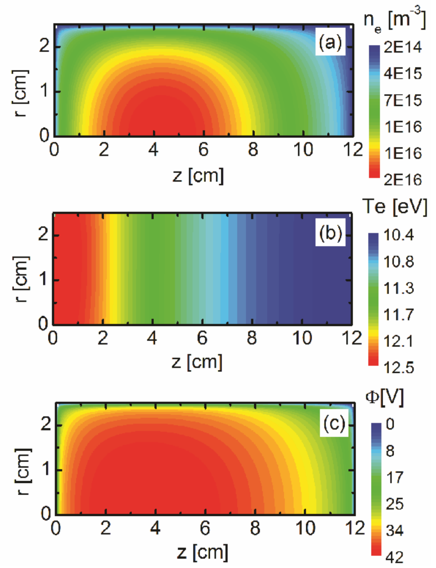

Figure 2. Spatial distribution of the electron density (a), of the electron temperature (b) and of the plasma potential (d), obtained without a probe at 10 mTorr.

Figure 2 shows the spatial distribution of the plasma parameters obtained at 10 mTorr without a probe. It is typical for low gas pressure discharges with localized power deposition: maxima of n_{e}, T_{e} and Φ close to the power deposition region, and remote plasma maintenance outside it, where the plasma parameters decrease.

The relative deviation of the electron density (Fig. 3) shows that with the probe immersed into the discharge n_{e} decreases in the first half of the discharge tube ($z < 6$ cm) and increases in its second part ($z > 6$ cm). Since this pattern shows up also at $U_{\mathrm{pr}} = U_{\mathrm{fl}}$ (Fig. 3(b)), it can be considered as an effect of the probe as a body immersed into the discharge. For the three values of U_{pr}, shown in Fig. 3, the region of the relative deviations which are below -10% is locked between the probe and the bottom of the tube at $z = 0$. In fact, there are values of $\Delta n_{\mathrm{e}}/n_{\mathrm{e}} \approx -60\%$ which are very close to the probe, in the region of the probe sheath. The highest values of $\Delta n_{\mathrm{e}}/n_{\mathrm{e}}$ in the second half of the tube ($z > 6$ cm) are roughly within 10% ($\Delta n_{\mathrm{e}}/n_{\mathrm{e}} < 15\%$). With the increase of U_{pr}, the entire pattern of $\Delta n_{\mathrm{e}}/n_{\mathrm{e}}$ shifts towards the bottom of the tube and the probe.

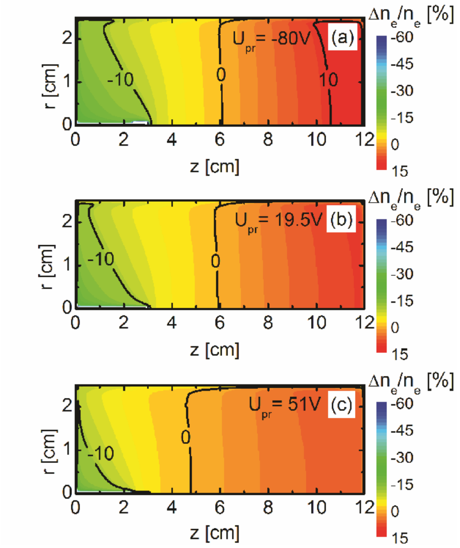

Figure 3. Spatial variations of the relative deviation in the electron density distribution obtained at: (a) U_{pr} = -80 V (in the ion-saturation current of the probe characteristic), (b) U_{pr} = 19.5 V (at the floating potential), and (c) U_{pr} = 51 V (in the electron-saturation current of the probe characteristic); p = 10 mTorr.

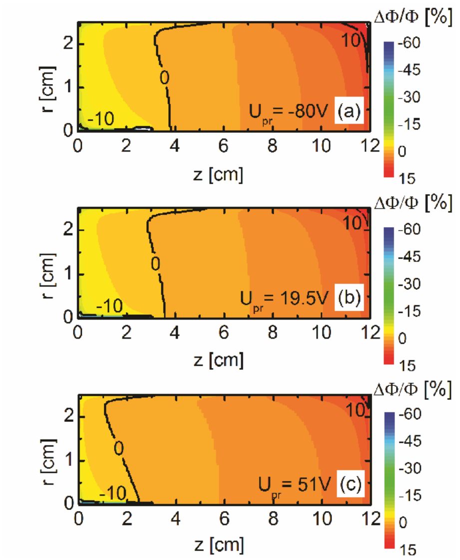

Figure 4. The same as in Fig. 3 but for the plasma potential.

This behaviour show evidence also in the spatial variations of the relative deviation of the plasma potential (Fig. 4). However, the values of $\Delta\Phi/\Phi < -10\%$ are strongly localized in the plasma sheath around the probe. Similarly to $\Delta n_e/n_e$, the increase of U_{pr} shifts the pattern of $\Delta\Phi/\Phi$ towards the bottom of the tube and the probe. The increase of Φ in the region on the right hand side of the ($\Delta\Phi/\Phi = 0$)-contour is again roughly within 10%.

The spatial variation of the relative deviation of the electron temperature, given in Fig. 5, shows a quite different behaviour compared to that of $\Delta n_e/n_e$ (Fig. 3) and $\Delta\Phi/\Phi$ (Fig. 4). A probe immersed into the discharge leads to an increase of T_e in the region close to the bottom of the tube. At U_{pr} = -80 V and $U_{pr} = U_{fl}$ (respectively, Figs. 5(a) and 5(b)) $\Delta T_e/T_e$ is positive, varying roughly within 2%. Thus, the probe (as a body) causes a total increase of the electron temperature. However, at $U_{pr} > \Phi$ a region of $\Delta T_e/T_e < 0$ appears in the second half of the tube at $z > 5$ cm.

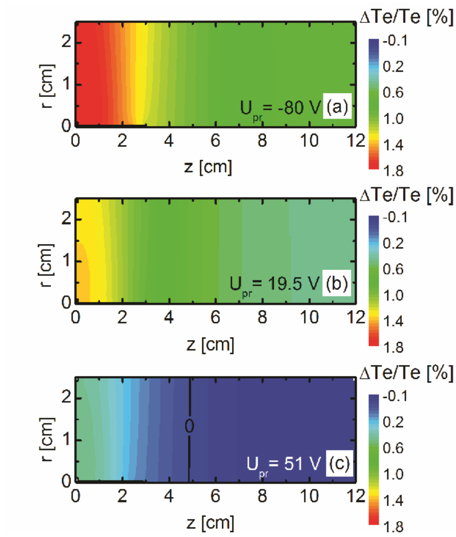

Figure 5. The same as in Fig. 3 but for the electron temperature.

In general, immersing the probe causes a drop of n_e and Φ and an increase of T_e in the first half of the tube, where the probe is located. According to the general trend in the gas-discharges behaviour, an increase of T_e accompanied with a drop of n_e means that the probe introduces additional losses of charged particles. The shift of the entire pattern of the relative deviation of the plasma parameters towards the probe with the increase of U_{pr} could be attributed to the reduction of the strong gradient of the plasma potential in the vicinity of the probe tip. The latter leads to the shift of the entire pattern of the plasma parameters towards the probe.

At higher gas pressure (50 mTorr, Fig. 6) the nonlocality in the discharge behaviour is not so strong and, as a result, the maximum of the electron density (Fig. 6(a)) is closer to the coil. Whereas at p = 10 mTorr the changes of $\Delta n_e/n_e$ cover both negative and positive values, at p = 50 mTorr the probe causes total lowering of n_e. Thus, in this case the influence of the probe on n_e in the region with relative deviation of the electron density above -10% is weaker. With the increase of U_{pr}, the region of $\Delta n_e/n_e < -10\%$ has behaviour similar to that at 10 mTorr: the entire profile of $\Delta n_e/n_e$ shifts towards the bottom of the tube and the probe. However, the ($\Delta n_e/n_e = -10\%$)-contour is more localized around the probe. Thus, although the spatial region of influence of the probe on n_e is different, the general trends in the pattern of $\Delta n_e/n_e$ are the same as at 10 mTorr.

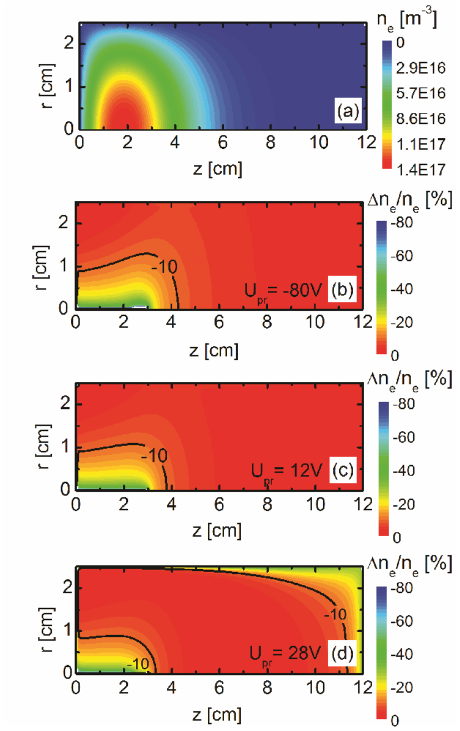

Figure 6. Spatial variations of the electron density (a) and its relative deviation obtained at (b) U_{pr} = -80 V (ion-saturation current), (c) U_{pr} = 12 V (floating potential), and (d) U_{pr} = 28 V (electron-saturation current). The gas-pressure is 50 mTorr.

4. Conclusions

Based on a 2D discharge model, the study shows the influence of a single Langmuir probe immersed into a small-radius discharge on the spatial distribution of the plasma parameters. The effect of the probe holder is marked off from that of the bias applied to the probe tip via comparison of results for the relative deviations of the plasma parameters obtained, respectively, at the floating potential and at a bias corresponding to the ion- and electron-saturation current regions in the I-V probe characteristic.

The main conclusion is that immersing the probe affects the plasma parameters not only locally, in the region of the plasma sheath (around the probe), but also in the entire discharge volume. However, the region of the relative deviations below -10% is in the vicinity of the probe. The overall deviations of the plasma parameters in the majority of the discharge volume are roughly within ±10%. The probe holder acts as an internal wall, introducing additional losses in the discharge and, thus, leading to lower electron density and higher electron temperature. The probe bias affects the spatial distribution of the plasma by modifying the plasma potential in the vicinity of the probe tip. As a result, a higher potential to the probe attracts the plasma towards it. With the increase of the gas pressure the influence of the probe on the plasma parameters is more localized in the vicinity of the probe.

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