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2D fluid-model simulations of plasma expansion

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Abstract. The study presents results from a 2D fluid-plasma model developed for description of the plasma production in two-chamber plasma sources (tandem–type of plasma sources). The model demonstrates the role of the particle and energy fluxes from the driver region for the plasma maintenance in the second chamber of the source. The influence of the applied power variation on the basic plasma parameters is outlined in the study.

1. Introduction

The tandem plasma sources consist of two chambers with different dimensions: a small driver region where the external rf power (e.g., inductively coupled) is applied and the plasma is produced, and a second – bigger – expansion-plasma chamber where the plasma exists due to particle and energy transport from the driver. The localization of the rf power deposition and the difference in the dimensions of the chambers determine the typical – for such sources – spatial distribution of the plasma parameters: high plasma density and electron temperature in the driver smoothly decreasing in the big chamber. Such a distribution of the plasma parameters is favourable for applications in plasma technologies [1, 2] and as negative hydrogen ion beam sources for use in fusion [3].

The complicated shape of the discharge vessel determines the increased complexity of the models of the tandem-type plasma sources. The longitudinal particle and energy fluxes, usually neglected in the models of discharges sustained in long tubes [4], play a crucial role here and, therefore, the models should be at least two-dimensional (2D). Also the widely used assumption for equality of the fluxes of electrons and positive ions could fail [5], and, thus, the dc field in the discharge should be obtained not from the ambipolar condition but from the Poisson equation.

This paper presents a 2D fluid-plasma model of a tandem type of a plasma source with a cylindrical geometry. An argon discharge at 50 mTorr is studied. The changes of the plasma parameters with the applied power are emphasized.

2. Basic equations

The basic set of equations consists of the continuity equations for electrons and ions

$$\operatorname{div} \vec{\Gamma}_{\mathrm{e,i}} = \frac{\delta n_{\mathrm{e,i}}}{\delta t}, \qquad (1)$$

the electron energy balance equation

$$\operatorname{div}\vec{\Gamma}_{\mathrm{T}} = P_{\mathrm{ext}} + e\vec{\Gamma}_{\mathrm{e}} \cdot \nabla\Phi + P_{\mathrm{coll}}, \tag{2}$$

and the Poisson equation

$$\Delta\Phi = \frac{e}{\varepsilon_0}\left(n_{\mathrm{e}} - n_{\mathrm{i}}\right). \tag{3}$$

In (1)-(3), $\delta n_{\mathrm{e,i}}/\delta t$ describes the particle production in ionization, n_{e} and n_{i} are the electron and ion densities and P_{ext} and P_{coll} are, respectively, the externally applied power and the electron energy losses in elastic and inelastic collisions. The term $e\vec{\Gamma}_{\mathrm{e}} \cdot \nabla\Phi$ describes the losses for maintenance of the dc field $\vec{E}$ (with a potential Φ) and e is the elementary charge; ε_0 is the vacuum permittivity. The fluxes of electrons [$\vec{\Gamma}_{\mathrm{e}} = b_{\mathrm{e}} n_{\mathrm{e}} \nabla\Phi - D_{\mathrm{e}} \nabla n_{\mathrm{e}} - D_{\mathrm{e}}^{\mathrm{T}} n_{\mathrm{e}}\left(\nabla T_{\mathrm{e}}/T_{\mathrm{e}}\right)$] and ions ($\vec{\Gamma}_{\mathrm{i}} = -b_{\mathrm{i}} n_{\mathrm{i}} \nabla\Phi - D_{\mathrm{i}} \nabla n_{\mathrm{i}}$) are obtained from the momentum equations. The first terms in the expressions for $\vec{\Gamma}_{\mathrm{e}}$ and $\vec{\Gamma}_{\mathrm{i}}$ specify the charged particle motion in the dc field (with $b_{\mathrm{e,i}}$ being the mobilities) and the second ones describe the role of the diffusion (with coefficients $D_{\mathrm{e,i}}$). Because of the significant change of the electron temperature T_{e}, the thermal diffusion (with coefficient $D_{\mathrm{e}}^{\mathrm{T}} \equiv D_{\mathrm{e}}$) is also included in $\vec{\Gamma}_{\mathrm{e}}$. The first term in the electron energy flux $\vec{\Gamma}_{\mathrm{T}} = -\chi_{\mathrm{e}} \nabla T_{\mathrm{e}} + (5/2) T_{\mathrm{e}} \vec{\Gamma}_{\mathrm{e}}$ accounts for the thermal conductivity (with coefficient χ_{e}) and the second one is the convective flux (the energy carried by the electron flux).

The modeling domain (half of the source) is as given in figures 1 and 2. The input power P_{ext}, assumed radially constant, is localized in the smaller radius ($R_1 = 2.25$ cm) chamber, at $z = (-2.5 \div -17.5)$ cm. The discharge vessel is with metal walls, at zero potential.

A more detailed description of the model is given in [5].

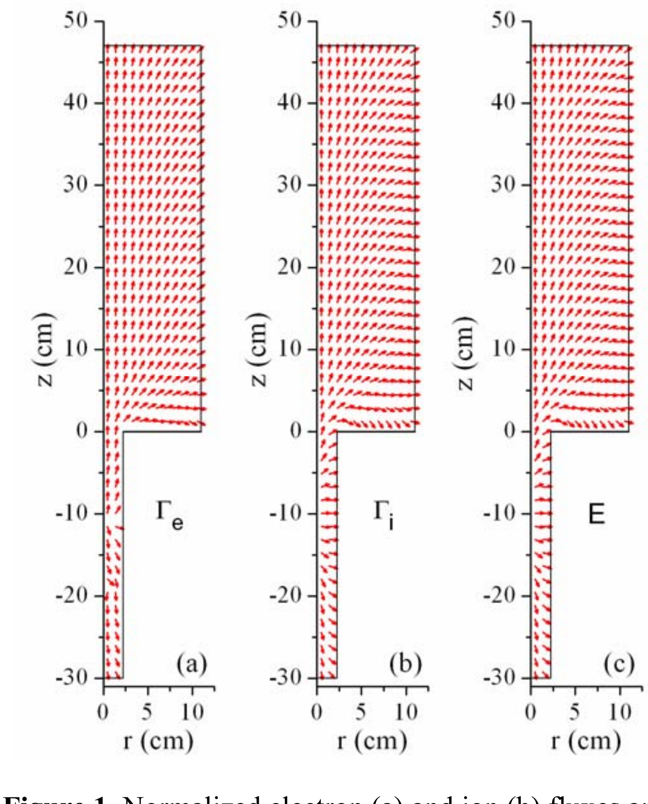

Figure 1. Normalized electron (a) and ion (b) fluxes and normalized dc electric field (c); total applied power P = 200 W.

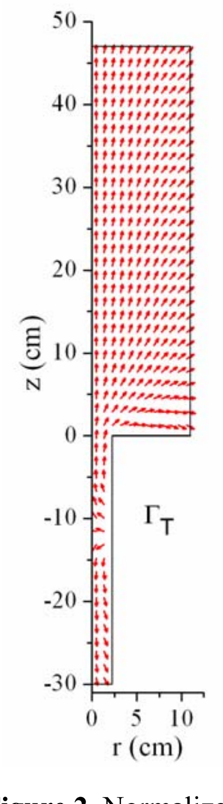

Figure 2. Normalized electron energy flux; $P = 200$ W.

3. Results

The results presented in this section are numerical solutions of the set (1)-(3). First the general behaviour of the particle and energy fluxes in the tandem plasma source is discussed and then the dependence on the applied power is analyzed.

The centre of the power deposition region is at z = -10 cm and this is the starting position of the fluxes of the electrons (figure 1(a)) and the ions (figure 1(b)), flowing both in the positive and negative z directions. In the driver, the ions move predominantly in the radial direction while the electrons move in the axial direction. Such behaviour is determined by the dc electric field (figure 1(c)). In the driver, the E_r-field is bigger than E_z and the (positive) ions are attracted to the walls. Contrariwise, the electrons are repelled from the walls and they move in the z-direction. The comparison of figures 1(b) and 1(c) shows that the ions follow the electric field and, therefore, the drift of the ions in the dc field determines the ion flux. The situation with the electrons is more complicated. The drift in the dc field and the diffusion are the most important factors forming the electron flux, acting, in general, in the opposite directions. The diffusion is the predominating process except for the regions $z = (-2.5 \div 8)$ cm and $z = (-15 \div -22)$ cm. However, in these regions the electron temperature changes fast (figure 3) and the role of the thermal diffusion increases. As a result, the sum of diffusion and thermal diffusion dominates over the drift motion in the dc field in the whole source.

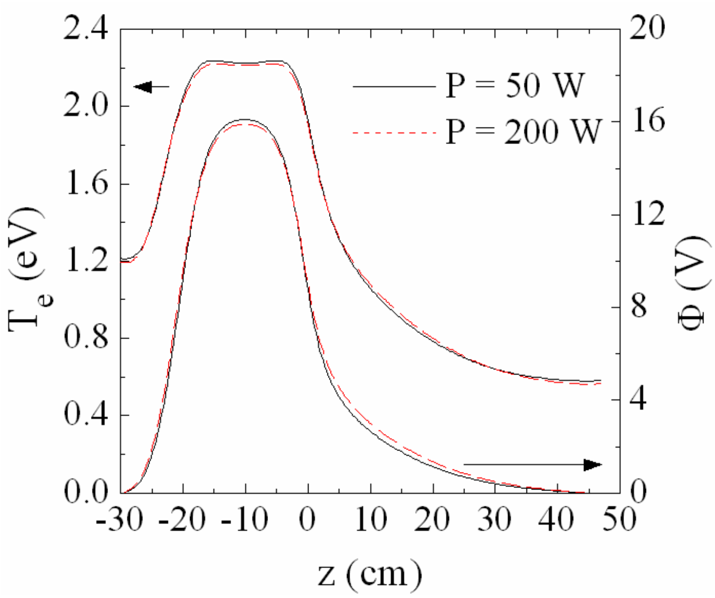

Figure 3. Axial profiles (at $r = 0$) of T_e and Φ.

The electron energy flux carries energy from the driver to the big chamber (figure 2). The conductive and convective fluxes are almost parallel, except for the driver region. In the driver the applied power is radially constant but the electron concentration decreases towards the walls. Therefore, an electron near the wall gains more energy than an electron near the axis and the temperature at the wall is a little bit higher. This energy is transferred to the central part of the tube via thermal conductivity, which explains the thermal flux directed from the wall to the axis, in the vicinity of $z = -10$ cm. At the same time a smaller convective flux is directed to the wall.

Figure 4 shows the energy balance at the axis. In the driver the externally applied power has a super-Gaussian profile centered at z = -10 cm with a width of 15 cm at half maximum. Such an axial shape of the power input is a good approximation of the power deposition in inductive discharges with cylindrical coils. As it has been mentioned, the radial thermal flux is also a power source in the central region of the driver. The inelastic collisions for excitation are the most important mechanism of losses in this region. The axial electron energy flux is created in the driver and, therefore, it also appears as losses. Its role changes in the expansion chamber where the axial electron energy flux is the only power source. The main losses there are through the radial electron energy flux and for sustaining the dc electric field. The low value of the electron temperature is the reason for the decreased importance of the collisions. Under such conditions, the relative role of the elastic collision increases. The extremely low losses for ionization indicate that the plasma in the expansion chamber exists mainly due to the particle transport from the driver.

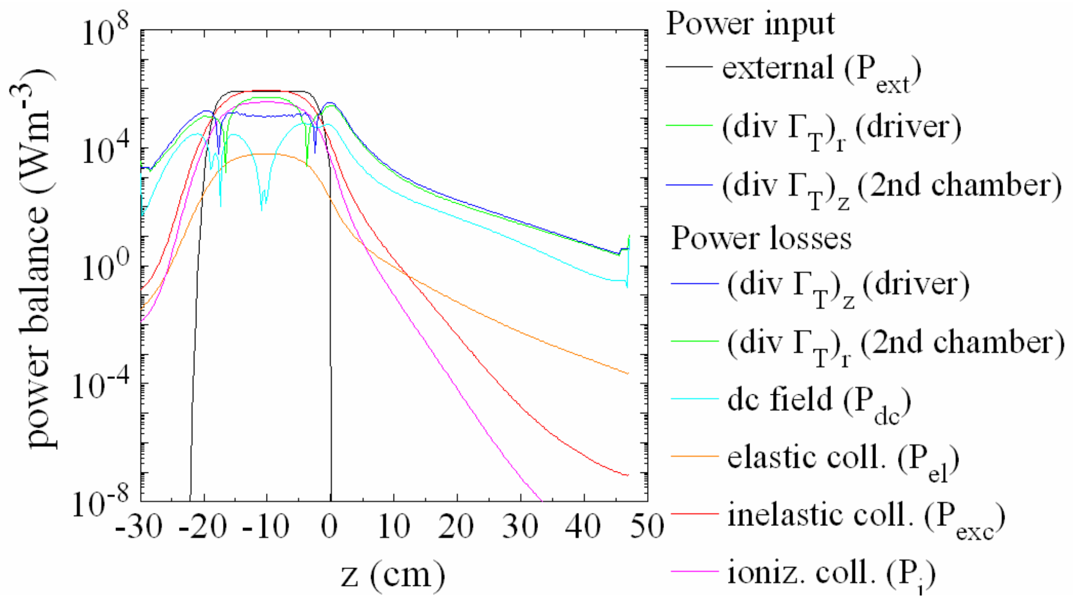

Figure 4. Power balance at $r = 0$ cm; $P = 200$ W.

Axial plasma density profiles are plotted in figure 5, for four values of the total applied power *P*. The maximum of the plasma density is in the region of the maximum power deposition. Outside this region the plasma density decreases because of the particle losses to the walls, mainly in the radial direction. The smaller radius of the first chamber causes higher particle losses and the plasma density profiles here are steeper compared to the expansion chamber. With the power increase, the plasma density in the driver increases almost linearly.

The electron temperature (figure 3) in the driver is almost constant at $z = (-2.5 \div -17.5)$ cm, smoothly decreasing to lower values in the expansion plasma

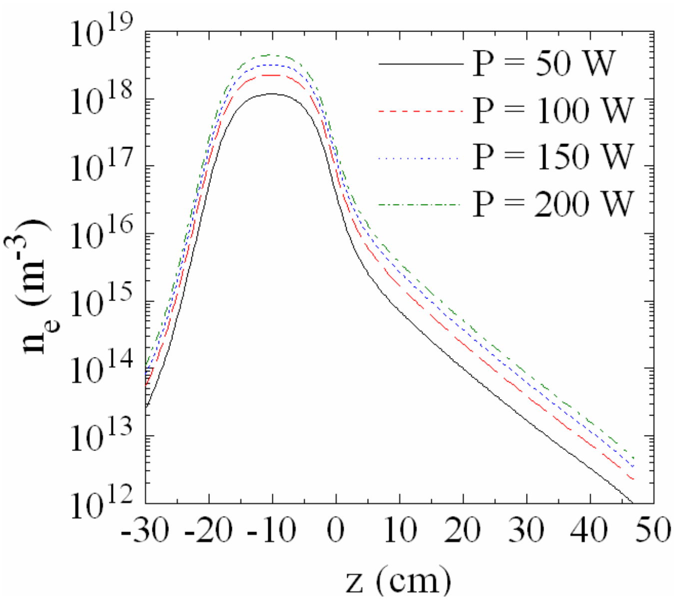

Figure 5. Axial profiles of the plasma density at $r = 0$.

chamber. The temperature is not sensitive to the changes of the power as it is typical for rf discharges in the case of saturated step ionization [4].

The potential of the dc field (figure 3) has a maximum in the driver, decreasing to zero on the metal walls. Similarly to the temperature it does not change significantly with the power variation.

The axial variation of the axial components of the electron (v_{ez}) and ion (v_{iz}) velocities are only slightly influenced by the applied power (figure 6). The maxima of v_{iz} are determined by the maxima of the dc field on both sides of the driver. The increase of v_{ez} in the second chamber is due to the decrease of the retarding – for the electrons – dc field.

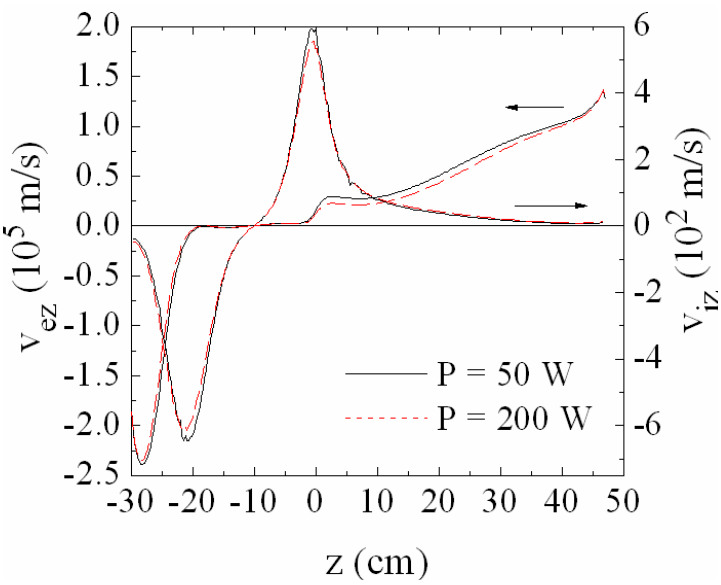

Figure 6. Axial variation (at $r = 0$) of the axial components of the electron and ion velocities.

4. Conclusion

The analysis presented here shows that the plasma density and the charged-particle fluxes increase almost linearly with the applied power, while the dependence of the electron temperature and of the potential of the dc field on the power is weak. Such a similarity with discharges maintained by power deposited all over the source can be attributed to the extremely low percentage (about 4%) of the applied power lost for maintenance of the plasma in the expansion volume.

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