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2D MODEL OF AN INDUCTIVELY COUPLED HYDROGEN DISCHARGE

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Introduction

The current interest in studying inductive discharges and, in particular, discharges in hydrogen is connected with their applications in the plasma processing technology and as ion sources for fusion-plasma heating. Moreover, the sources used in the gas-discharge applications are with a complicated design, usually consisting of two chambers with a localized power deposition to the first one and plasma expansion in the second chamber. This has provoked the interest in modelling of remote plasmas [1, 2] which requires description within at least two-dimensional (2D) models. Recent 2D models [3, 4] of argon and hydrogen discharges sustained in two-chamber plasma sources with metal walls and different dimensions in the radial and axial directions have demonstrated the existence of a gas discharge regime with a net dc current in a rf discharge. This dc current results from a solenoidal flux ($\mathrm{div}\vec{\Gamma} = 0$, with $\vec{\Gamma} = \vec{\Gamma}_{\mathrm{e}} - \vec{\Gamma}_{\mathrm{i}}$ being the difference between the electron and ion fluxes) flowing in the discharge. Moreover, a vortex type of a solenoidal flux has shown also evidence in hydrogen discharges [4].

This study is an extention of the models in Refs. [3, 4] towards completing a self-consistent 2D fluid-plasma model. The model is limited to the description of a hydrogen discharge in a source with a simple configuration: discharge in a single-chamber vessel. However, it is self-consistent specifying description of the rf power deposition in inductive discharges with a cylindrical coil. The latter replaces the radially homogeneous power deposition assumed in Refs. [3, 4]. The results show again a regime with a dc current in a rf discharge: Regardless of the relatively simple geometry, the solenoidal flux – in its form of a vortex flux – appears even in the region of the rf power deposition. The spatial distribution of the rf field and of the power deposition to the discharge are also described.

Description of the model

The modelling domain is a discharge tube with metal walls, with a radius $R = 2.25$ cm and a length of 25 cm. The discharge is in hydrogen. The results presented further on are at gas pressure $p = 30$ mTorr and total applied power $P = 500$ W at frequency $f = 27$ MHz. The plasma description is based on the fluid theory involving the continuity equations

$$\frac{\partial n_j}{\partial t} + \nabla \cdot \vec{\Gamma}_j = \frac{\delta n_j}{\delta t} \tag{1}$$

of electrons ($j = \mathrm{e}$), the three types of positive hydrogen ions ($j = 1,2,3$ for H^+, H_2^+ and H_3^+) and hydrogen atoms ($j = \mathrm{H}$), the electron energy balance equation

$$\frac{3}{2}\frac{\partial}{\partial t}(n_\mathrm{e}T_\mathrm{e}) + \nabla \cdot \vec{J}_\mathrm{e} = Q - P_{(\mathrm{coll})} - e\vec{\Gamma}_\mathrm{e} \cdot \vec{E}_\mathrm{dc}, \tag{2}$$

the Poisson equation

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

and the expression for the gas pressure.

In (1)–(3), n_j are the corresponding densities, T_e is the electron temperature (in energy units) and $\vec{E}_\mathrm{dc} = -\nabla\Phi$ is the dc electric field formed in the discharge. Drift-diffusion and thermal-diffusion fluxes complete the electron flux $\vec{\Gamma}_\mathrm{e}$, the ion fluxes $\vec{\Gamma}_{j=1-3}$ are drift-diffusion fluxes and the flux of the hydrogen atoms is a diffusion flux.

The electron energy flux $\vec{J}_\mathrm{e}$ includes both conductive and convective fluxes; Q is the heating in the rf field. The processes for particle production and losses ($\delta n_j/\delta t$) in (1) and the processes determining the electron energy losses in collisions $P_{(\mathrm{coll})}$ in (2) are the same as in Ref. [4]. The boundary conditions are also given there.

The external rf power is applied via 9 turns coil positioned between $z = 8.4$ cm and $z = 16.6$ cm on the figures below. In the model, the current in the coil is simulated by a current on the ($r = 2.25$ cm)-surface with a given value at the position of the turns of the coil and a zero value between them and outside the coil. The Maxwell's equations reduced to the equation

$$\frac{1}{\mu_0}\nabla \times \left(\nabla \times \vec{A}\right) + \left(\mathrm{i}\omega\sigma - \omega^2\varepsilon_0\right)\vec{A} = 0 \tag{4}$$

for the vector potential $\vec{A}$ are solved; the plasma conductivity σ is calculated by using the plasma density obtained in the gas discharge part of the model. In (4) $\omega = 2\pi f$ is the frequency of the rf field. The other notation is standard.

Results

Figures 1 and 2 show the self-consistent structure of the discharge stemming from the gas-discharge and electrodynamical description: results (Fig. 1) for the spatial distribution of the plasma parameters and of the direction of the fluxes and results (Fig. 2) for the spatial distribution of the amplitude $|E_\varphi|$ of the rf electric field, of the current density j_φ and of the Joule heating Q as well as for the direction of the magnetic field $\vec{H}$.

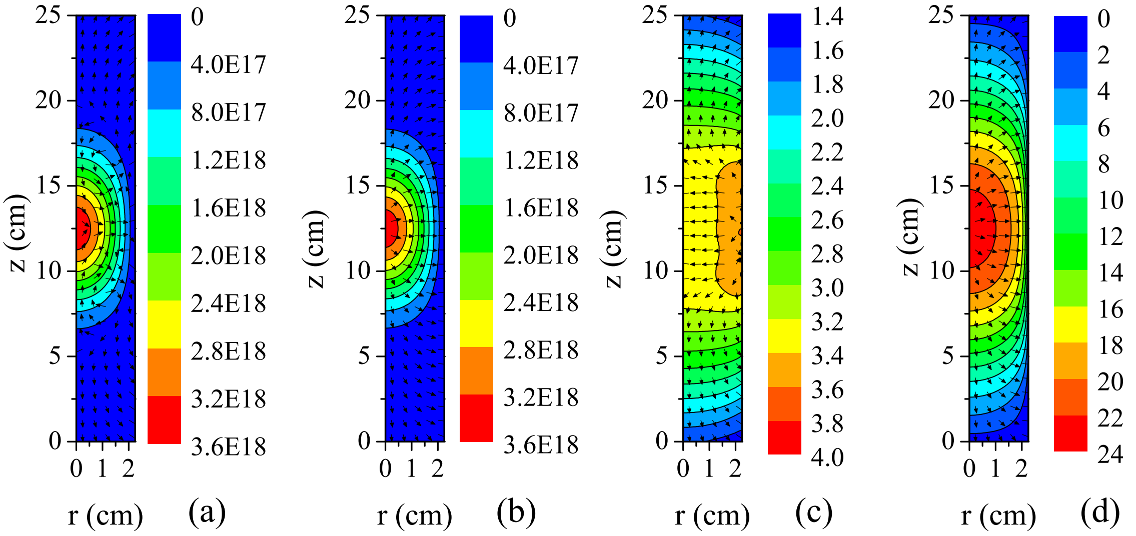

Figure 1. Spatial distribution and direction, respectively, of n_e [m^{-3}] and $\vec{\Gamma}_e$ in (a), of n_1 [m^{-3}] and $\vec{\Gamma}_1$ in (b), of T_e [eV] and $\vec{J}_e$ in (c) and of Φ [V] and $\vec{E}_{dc}$ in (d).

The electron density has its maximum at the centre $z = 12.5$ cm of the power-deposition region (Fig. 1(a)). The electron flux is directed towards the walls, having two regions of vortices centered at about $z \sim 8$ cm and $z \sim 16$ cm. The H^+-ions appear as the dominating type of ions. The spatial distribution of their concentration follows that of the electrons (Fig. 1(b)), ensuring the quasi-neutrality. Since the maximum of Q is close to the wall (Fig. 2(c)) and the maximum of n_e is on the axis, an electron near the wall gains more energy. This determines the higher electron temperature there (Fig. 1(c)). The electron energy is transferred from this region to the whole plasma volume by $\vec{J}_e$. This flux (Fig. 1(c)) is directed first from the wall to the axis and then to the regions outside the coil. The maximum of Φ is in the centre of the discharge (Fig. 1(d)). Because of the constant potential on the metal walls ($\Phi = 0$) the potential difference between the centre of the discharge and each of the walls is the same. This means that due to the different size in the radial and the axial directions the radial dc electric field is stronger than the axial one. This field is accelerating for the ions and retarding for the electrons. Therefore, the positive ions leave the plasma mainly in the radial direction while the electrons move easier against the weaker axial field. As a result, the flux $\vec{\Gamma} = \vec{\Gamma}_e - \sum_{j=1}^{3} \vec{\Gamma}_j$ (Fig. 3) is non-zero determining a dc current in the plasma. Since the production and the losses of electrons and positive ions are equal to each other, the flux $\vec{\Gamma}$ is a solenoidal flux ($\mathrm{div}\vec{\Gamma} = 0$).

Behaviour typical for inductive discharges with cylindrical coil results from the electrodynamical description: skin effect shown by the rapid decrease of the E_φ-amplitude inside the plasma (Fig. 2(a)), a magnetic field directed, inside the coil, parallel to the axis (Fig. 2(a)) and j_φ and Q concentrated in the outer region of the discharge (Figs. 2(b) and (c)). The nine maxima

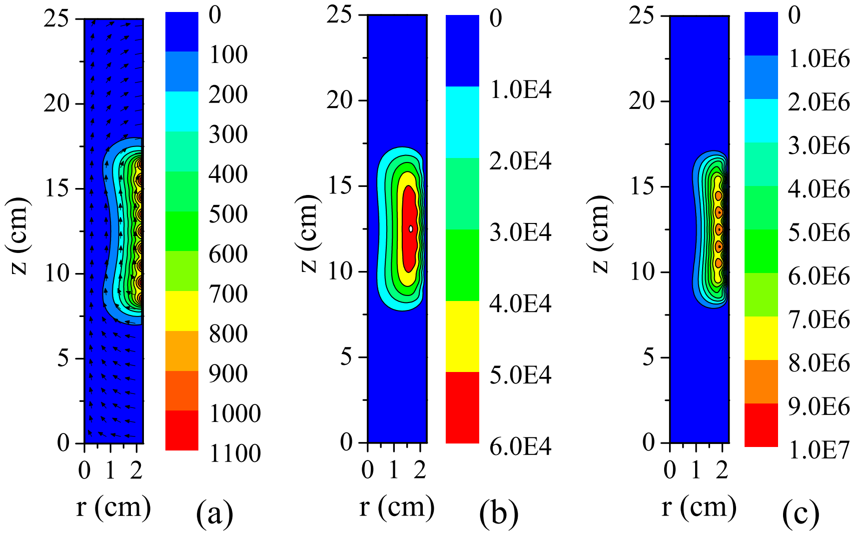

Figure 2. Spatial distribution of the amplitude of E_φ [V/m] and the direction of $\vec{H}$ in (a) and spatial distribution of j_φ [A/m^2] (b) and Q [W/m^3] (c).

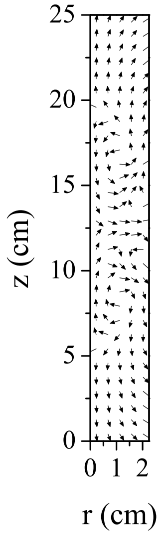

Figure 3. Direction of the $\vec{\Gamma}$-flux.

in the spatial distribution of E_φ and Q correspond to the positions of the nine turns of the coil. Compared to the electric field, the current density is shifted to the axis, due to the low electron density near the wall and, therefore, to the low conductivity there. The power deposition (Fig. 2(c)) keeps the features of the spatial distribution of E_φ and j_φ.

Conclusion

The study presents a self-consistent 2D model of an inductively driven discharge in hydrogen. The results show a regime with a dc current in a rf discharge appearing due to a solenoidal flux $\vec{\Gamma} = \vec{\Gamma}_e - \vec{\Gamma}_i$. The vortex-type of a $\vec{\Gamma}$-flux discussed before [4] as a behaviour in the expanding plasma region of a two-chamber plasma source now shows up in the rf power deposition region. The electrodynamical description completing the model provides the spatial distribution of the rf field and of the power deposition in the plasma.

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