2D self-consistent model of a hydrogen discharge inductively driven by a planar coil

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In the 2D-model of a hydrogen discharge presented in the study electrodynamical description of a planar-coil inductively-driven discharge is coupled to a fluid-plasma model description. The discussion on the results stresses on the efficiency of the discharge as a source of volume-produced negative ions as well as on the manner of the description of the rf power deposition.

The use of the large-radius planar-coil inductively-driven discharges in the plasma processing technology has been the motivation for the extended activity on their modelling, started in the 90's of the last century [1,2]. A recent concept [3] for a design of a source of volume-produced negative-hydrogen ions as a matrix source has taken into consideration the bahaviour of small-radius planar-coil inductively-driven discharges. Being in these trends, the study extends a 2D model [4] of small-radius hydrogen discharges by self-consistent coupling of the gas-discharge description (with account for the negative ions) with electrodynamical description of an inductive driving by a planar coil.

Based on the fluid plasma theory, the gas-discharge part of the model involves the continuity equations for electrons, the three types of the positive ions (H^+, H_2^+ and H_3^+), hydrogen atoms, negative ions (H^-) and for the fourteen vibrationally excited states (H_2(v=1–14)) of the hydrogen molecules, from which the negative ions are produced via electron attachment, as well as the electron energy balance and the Poisson equation (for more details, see Ref. [5]). The electrodynamical description is involved through the equation

$$\frac{1}{\mu_0}\vec{\nabla}\times(\vec{\nabla}\times\vec{A})+(\mathrm{i}\omega\sigma_{\mathrm{pl}}-\omega^2\varepsilon_0)\vec{A}=0 \qquad (1)$$

for the vector potential $\vec{A}$ of the high-frequency magnetic field $(\vec{B}=\vec{\nabla}\times\vec{A})$ with a boundary condition for a surface current at the wall where the coil is positioned, the latter presented by intercrossing of Heaviside functions at the position of each turn of the three-turn coil considered; $\omega=2\pi f$ is the rf frequency, σ_{pl} is the plasma conductivity and ε_0 and μ_0 are, respectively, the vacuum permittivity and susceptibility. The coupling of the gas-discharge and electrodynamical parts of the model is via the absorbed power $Q=(1/2)(\mathrm{Re}\,\sigma_{\mathrm{pl}})|E_\varphi|^2$ in the electron energy balance (where the rf field $\vec{E}=\mathrm{i}\omega\vec{A}$ comes out from the electrodynamical description) and via $\sigma_{\mathrm{pl}}(n_e)$ in (1), where the electron density n_e is determined in the plasma description.

The results from the model (Figs. 1 and 2) are for gas pressure p = 20 mTorr and total absorbed power P_{abs} = 1.9 kW at f = 27 MHz. The radius of the discharge is R = 3 cm and its length is L = 12.5 cm. The results for the electron density n_e and temperature T_e as well as for the potential Φ of the dc electric field (Fig. 1) are as it should be expected for a planar-coil driven discharge where the rf power deposition (Fig. 2(c)) is localized close to the front wall (z = 0) of the discharge vessel: a maximum of T_e close to z = 0, maxima of n_e and Φ at the discharge axis (r = 0), shifted from z = 0, and remote plasma maintenance outside the region of the power deposition determining nonlocality of the discharge behaviour (importance of the fluxes). In agreement with the results for small-radius hydrogen discharges inductively driven by a cylindrical coil [3, 5] there is a strong accumulation of H^- (Fig. 1(d)) in the region of the maximum of Φ, due to their flux Γ_n in the dc electric field E_{dc}. This is an effect of the small-radius of the discharge: E_{dc} is strong over the entire discharge and the discharge radius R is a survival length for the ions.

The rf electric field E_φ (Fig. 2(a)), being concentrated around the turns of the coil at z = 0, penetrates into the plasma over a skin depth of about 0.3 cm. The maxima of the rf current j_φ and Q are also at the radial positions of the turns of the coil, however, shifted into the plasma since they depend on both E_φ and n_e.

The validity of using a half of a super-Gaussian profile as an approximation for the rf power deposition to

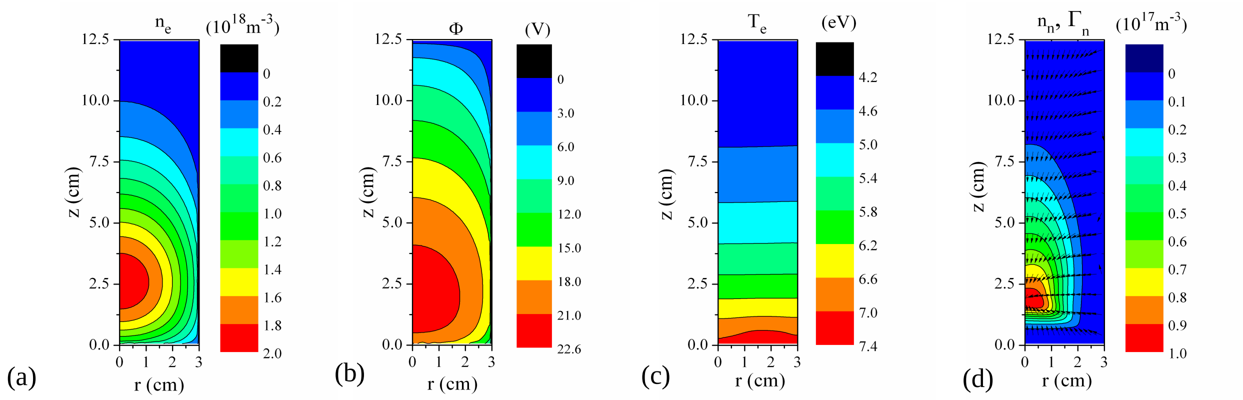

Fig. 1: 2D plots of the spatial distribution of n_e (a), Φ (b), T_e (c) and of the density n_n of the negative ions (d) and their flux Γ_n (the arrow plot in (d)).

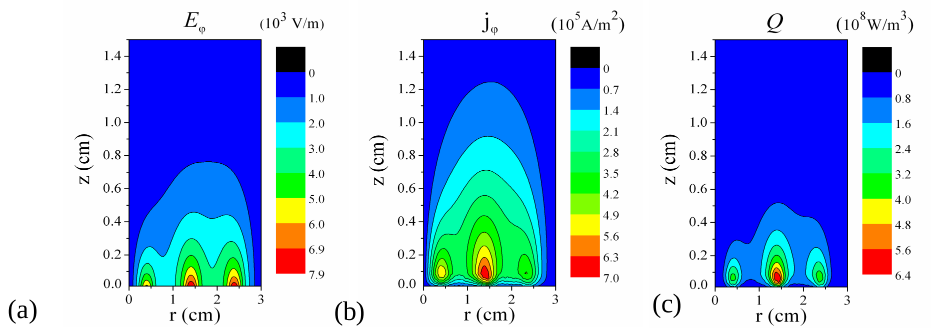

Fig. 2: Spatial distribution of the rf electric field (a), of the rf current density j_φ (b) and of the absorbed power Q (c) presented over an axial length up to z = 1.5 cm.

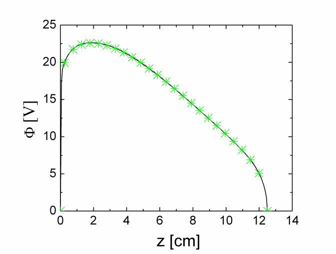

Fig. 3: Comparison of the results for $\Phi(r = 0,z)$ obtained from the self-consistent model (symbols) and with a half of a super-Gaussian profile (with a half-width of 0.3 cm) of P_{abs} (solid curve); P_{abs} = 1.9 kW.

planar-coil discharges has been checked by comparison (Fig. 3) with the results from the self-consistent model. The very good agreement of the results for the spatial distribution of the plasma characteristics shows that the approximation is a proper one. Moreover, the choice of the value of the length of the profile is not crucial at all (e.g. twice larger half-width of the profile than that in Fig. 3 does not make also difference).

In conclusion, the results from the self-consistent model of a planar-coil driven hydrogen discharge are in a support to the concept for the matrix source [3]. In addition, a super-Gaussian-profile approximation of the localized rf power deposition to planar-coil discharges is a proper one for describing the plasma behaviour.

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