

The Radial Properties of High-Frequency Gas Discharges Sustained by Surface Waves in the Presence of an External Magnetic Field

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We consider both metal and dielectric cylindrical tubes in which a plasma column of radius R is sustained by a surface wave (SW). An external static magnetic field \vec{H}_0 is applied in axial direction. It is assumed that the plasma is quasineutral. The stationary argon plasma is considered. It is believed that the plasma is singly and low ionized. It is assumed that plasma density variation along plasma column axis is small. In this case the set of equations for description of the gas discharge properties in radial direction reduces to the set of one-dimensional ordinary differential equations in radial coordinate r . The set consists of charged particle balance equation and energy balance equation for electrons. The charged particle balance equation can be presented in the form [1]:

$$\frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial}{\partial r} (D_{\perp} n) \right) + v^i n = 0, \quad (1)$$

where n is charged particle density, D_{\perp} - diffusion coefficient in radial direction. In the case of ambipolar diffusion regime $D_{\perp} = D_{A\perp} \approx 2T_e / (m_i v_{in} (1 + 2\omega_i \omega_e / (v_{in} v_{en})))$, for anomalous diffusion regime $D_{\perp} = D_{B\perp} \approx T_e c / (16eH_0)$. Here T_e - electron temperature, e - electron charge, c - light velocity, m_i - ion mass, ω_e and ω_i are cyclotron frequencies for electrons and ions, respectively, v_{in} is ion-neutral collision frequency. For calculation of v_{in} we used the expression, presented in [2]. The electron-neutral collision frequency v_{en} was calculated under assumption of Maxwell energy distribution of electrons. The ionization frequency v^i under numerical calculation of the discharge parameters was taken in the form, presented in [3]. For determination of diffusion regime in magnetoplasma which is contained in dielectric tube we used the results of the paper [4]. In the case when the plasma is surrounded by metal walls the short-circuit diffusion regime takes place and we believed that diffusion in radial direction is determined by L-diffusion coefficient [5]: $D_{\perp} = D_{L\perp} \approx 2T_e / (m_i v_{in} (1 + \omega_i^2 / v_{in}^2))$. Under conditions considered in the paper the influence of volume recombination on the radial properties of gas discharge is small and the recombination is neglected.

The energy balance equation for electrons can be presented in the following form [1]:

$$\frac{3}{2} n u_{dr} \frac{\partial T_e}{\partial r} + n T_e \frac{1}{r} \frac{\partial (r u_{dr})}{\partial r} + \frac{1}{r} \frac{\partial (r q_r)}{\partial r} = -\frac{3}{2} n \kappa_{ea} v_{ea} T_e + n v_{en} m_e u_e^2 \quad (2)$$

where $\kappa_{ea} v_{ea} \approx (2m_e / m_n) v_{en} + \sum_j v_j U_j / T_e + v^i U^i / T_e$; v_j - the excitation frequency

from ground state to level j with a threshold energy U_j , U^i - the ionization threshold energy. For our calculations we have taken into account the excitation from ground state to $4s$ and $4p$ levels. To calculate the excitation frequencies we have used the formulas presented in [3]. m_n and m_e are masses of neutral atom and electron, u_e is electron oscillation velocity in the

SW field coverage over period of the oscillations, $u_{dr} \approx -\frac{1}{n} \frac{\partial(D_{\perp} n)}{\partial r}$ - drift velocity of electrons in radial direction, q_{er} -radial component of electron heat flow density: $q_{er} \approx -2,5 \partial T_e / \partial r \times n T_e v_{en} / (m_e (\omega_e^2 + v_{en}^2))$. The square of electron oscillation velocity averaged over period of the oscillations in the SW field can be found from hydrodynamic equations and presented in the form: $u_e^2 = e^2 E_{eff}^2 / (2m_e^2 \omega^2)$, where E_{eff} is effective electric field. For the high-frequency SW it is expressed through components of SW electric field, electron cyclotron and SW frequencies. In the case when symmetric SW propagates in plasma column along plasma- dielectric (or metal) interface the components of SW electric fields decrease from the interface to the center of plasma column and in the first approximation the E_{eff} can be presented in the form: $E_{eff} = A I_0(\kappa r)$, where A is constant value of radial coordinate r , κ is reverse skin depth of the SW. For determinacy we have chose that $\kappa = 2,5 / R$. In the case when the SW propagates along a metal antenna immersed in the center of plasma column the components of SW electric field decrease from the center of discharge. Thus we have presented the effective electric field in the form $E_{eff} = B / r$ for this case. Here B is constant value.

To solve the equations (1)-(2) the following boundary conditions are used: 1) in the center of the discharge radial gradients of electron density and temperature are equal to zero when SW propagates along outer interface of plasma column and in the case of uniform heating; 2) u_{dr} is equal to $\sqrt{T_e / m_i}$ on the plasma column boundaries under small values of magnetic field ($\omega_e \omega_i \ll v_{en} v_{in}$). But in the case of large values of magnetic field ($\omega_e \omega_i \gg v_{en} v_{in}$) the flows from plasma on the walls of the discharge are equal $\Gamma \approx n \rho_e v_{en}$ (where ρ_e -larmor radius); 3) electron heat flow density under small values of magnetic field at $r = R$ is as indicated in [1]: $q_e \approx T_e (2 + \ln \sqrt{m_i / m_e}) u_{dr} n$. But in the case of strong magnetic field we have believed that at $r = R$ $q_e \approx T_e n \rho_e v_{en}$. The analogous conditions have been used at plasma-metal antenna interface in the case of presence of metal antenna in plasma. For L-diffusion regime we believed that in all cases considered the boundary conditions correspond to the case of small magnetic field.

The problem is solved numerically by method of finite differences using integro-interpolation method [6]. Radial profiles of electron density and electron temperature have been obtained for different types of heating and diffusion regimes. The some results of the study for electron densities are presented in the Fig. 1-6. In the Fig.1 the dependencies of normalized electron density n / n_0 (n_0 -maximal electron density in plasma column) from radial coordinate r are shown. The curves in fig.1 have been obtained for argon gas pressure $P = 0,5 \text{ Tor}$, $H_0 = 300 \text{ Oe}$, $R = 1,25 \text{ cm}$. The L-diffusion regime is considered. Under calculations

of the plasma parameters the value $K = \int_0^R n m_e u_e^2 \pi r dr$ was fixed. K characterizes the Joule

heating of the electrons by the HF field in the plasma per unit length. The curves in the fig.1 have been obtained for $K = 4 \times 10^{-4} \text{ erg / cm}$. The curve 1 corresponds to the case when the metal antenna of radius $r_a = 0,05 \text{ cm}$ exciting the SW is situated in the center of plasma column ($E_{eff} \sim 1 / r$, $n_0 = 1,1 \times 10^{11} \text{ cm}^{-3}$). The curve 2 corresponds to the case of uniform

heating of the plasma ($n_0 = 2,8 \times 10^{11} \text{ cm}^{-3}$), the curve 3 is obtained in the case when $E_{\text{eff}} \sim I_0(2,5r/R)$ (in this case $n_0 = 2,1 \times 10^{11} \text{ cm}^{-3}$). From the fig.1 one can see that if $E_{\text{eff}} \sim I_0(2,5r/R)$ then the profile of plasma density becomes fatter in the region close to the axis than that in the isothermal heating of plasma column. The maximum of plasma density displaces from the center of discharge in the case when $E_{\text{eff}} \sim 1/r$. Near plasma boundaries the electron density is minimal. The all curves in the fig.2-6 are obtained for $E_{\text{eff}} \sim I_0(2,5r/R)$. In the fig.2 the results of studies of normalized plasma density in dependence of plasma column radius are presented under the L-diffusion regime. The curve 1 corresponds to the case when $R = 1.25 \text{ cm}$, $n_0 = 4.1 \times 10^{11} \text{ cm}^{-3}$, the curve 2- $R = 2.5 \text{ cm}$, $n_0 = 2.8 \times 10^{11} \text{ cm}^{-3}$; the curve 3 - $R = 5.0 \text{ cm}$, $n_0 = 2.0 \times 10^{11} \text{ cm}^{-3}$. The all curves are obtained at $H = 500 \text{ Oe}$, $P = 0.1 \text{ Tor}$, $K = 10^{-2} \text{ erg/cm}$. Under calculation of the electron temperature in dependence of plasma column radius we have obtained that the electron temperature decreases with increasing of plasma column radius. Due to this fact the decreasing of diffusion coefficients with increasing of plasma column radius is observed and consequently the normalized plasma density gradients near plasma-metal interface increase with increasing of plasma column radius. In the fig.3 the dependencies of normalized plasma density on argon gas pressure are presented. The curves are obtained for L-diffusion regime at $R = 1.25 \text{ cm}$, $H = 500 \text{ Oe}$, $K = 4 \times 10^{-4} \text{ erg/cm}$. Curves 1;2;3;4 have been obtained under pressure of neutral gas: $P = 0.05; 0.1; 0.5; 5 \text{ Tor}$, respectively. For these pressures we have obtained that the electron density in the center of discharge $n_0 = 0.71; 1.7; 20; 710 \times 10^{10} \text{ cm}^{-3}$, correspondingly. From fig.3 one can see that the plasma density profiles become more homogeneous with decreasing of gas pressure. The results of our studies have showed that the electron temperature decreases with gas pressure growing up. In the fig.4 the curve 1 corresponds to L-diffusion regime ($n_0 = 4 \times 10^{11} \text{ cm}^{-3}$), 2- ambipolar diffusion regime ($n_0 = 4.7 \times 10^{11} \text{ cm}^{-3}$). The curves are obtained for $H = 300 \text{ Oe}$, $P = 0.1 \text{ Tor}$, $K = 10^{-2} \text{ erg/cm}$. From fig.4 it follows that in the L-diffusion regime the profile of plasma density becomes slightly fatter in comparison with the case of ambipolar diffusion regime. In the fig.5 the curve 1 corresponds to L-diffusion regime ($n_0 = 1,8 \times 10^{11} \text{ cm}^{-3}$), 2- anomalous diffusion regime ($n_0 = 4.5 \times 10^{11} \text{ cm}^{-3}$). The curves are obtained for $H = 700 \text{ Oe}$, $P = 0.05 \text{ Tor}$, $K = 10^{-2} \text{ erg/cm}$. From fig.5 it follows that in the L-diffusion regime the plasma is more uniform in radial direction in comparison with the case of anomalous regime. It was observed that the electron temperature was slightly smaller in the case of anomalous regime in comparison with the case of L-diffusion regime. In the fig.6 the electron density profiles in dependence of magnetic field value are presented. The curves have been obtained for anomalous diffusion regime at $P = 0.1 \text{ Tor}$, $K = 10^{-2} \text{ erg/cm}$. The curves 1,2,3 correspond to the cases $H = 500, 700, 900 \text{ Oe}$, correspondingly. We have obtained that the electron temperature decreases with increasing of magnetic field value and due to this fact the plasma density growing is observed with increasing of magnetic field value.

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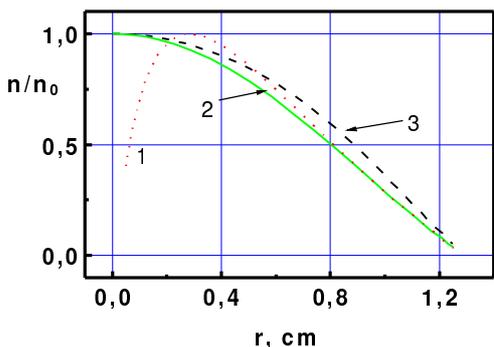


Fig.1 Normalized electron density profiles in dependence of type of heating.

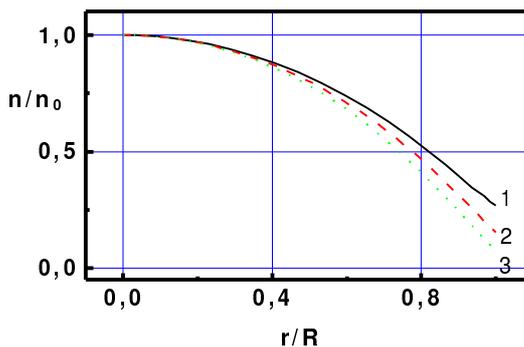


Fig. 2. Normalized electron density profiles in dependence of plasma column radius.

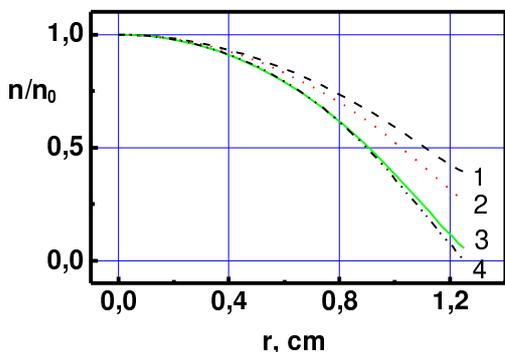


Fig.3 Normalized electron density profiles in dependence of neutral gas pressure.

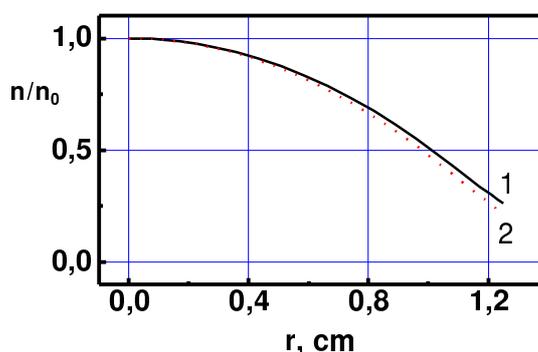


Fig. 4. Normalized electron density profiles in dependence of diffusion type.

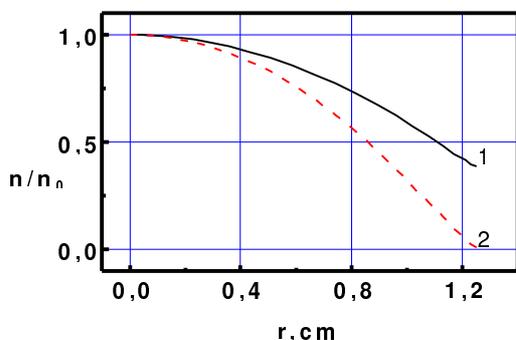


Fig.5 Normalized electron density profiles in dependence of diffusion regime.

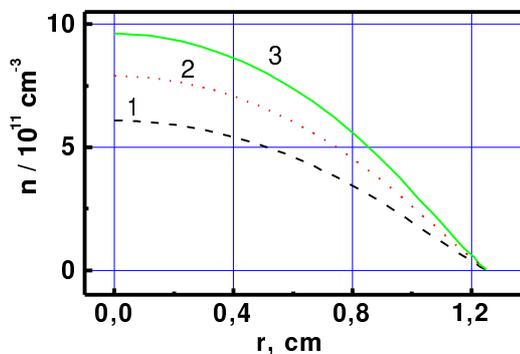


Fig. 6. Normalized electron density profiles in dependence of magnetic field value.