Studies of the RF Energy Delivery Mechanism and Its Reformation in the Low Pressure ICP Discharge

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Abstract— The model of a cylindrical inductively coupled plasma (ICP) discharge based on movable current layers travelling towards the axis of discharge space from the steady-state skin sheath at the external plasma boundary has been proposed. Current layers act like magnetic electrostatic traps catching electrons with small pinch-angles that are responsible for gas atom ionization. Movement of the layers induces electric field excites currents. At the optimal driving frequency magnetic field of a definite sign fills all discharge space during current half-period in the process of convective diffusion and eventually it is replaced by the field of opposite sign. Ohmic losses in the current layers are compensated by annihilation of magnetic field. The layers are formed by the Hall Effect while their boundary areas are shaped in a forceless magnetic field. They have form of one-turn spirals and their pairs are short-circuited in the edge plasma areas.

Concentration of trapped layer particles is determined from the equation for trapped electrons entering and leaving the layer by way of single-shot Coulomb collisions at the pinch-angle.

Discharge power loss, ion energy price and electron temperature are calculated at different argon pressures for the discharge chamber of 35 cm external radius. Comparison with published experimental data showed that the proposed model satisfactorily describes the main ICP discharge characteristics.

1. INTRODUCTION

RF inductively coupled plasma (ICP) discharge has been used on a wide scale in modern ion thrusters and in plasma technologic systems [1, 2]. Different models of the RF energy delivery mechanisms and its absorption based on collision and ionization processes have been proposed in numerous theoretical and experimental studies [3–5]. For ICP discharge at moderate and low gas pressures transformer analogy of the antenna coil-plasma magnetic coupling should be corrected to find optimal discharge driving frequency influencing ionization processes. Note that formulation and solution of the self-consistent problem dealing with calculations of ICP discharge plasma parameters that depend on design and operational conditions like discharge dimension, gas flow rate, its pressure and discharge power, are still unknown. The solution of this problem should result in optimal driving frequency, electron and ion currents, plasma resistance, electron temperature and ion energy price which is necessary to optimize ICP discharge system. This is what constitutes the goal of the present work.

Novelty of the proposed ICP discharge model consists of ionization mechanism within a movable current layer travelling from the contiguous to an antenna coil discharge skin sheath towards the axis of the internal space. These current layers form circuits that are short-circuited in the end face plasma areas.

2. PHYSICO-MATHEMATICAL MODEL OF AN ICP DISCHARGE

2.1. Convectional Transfer of Magnetic Field

From the magnetic induction equation

$$\frac{\partial \vec{B}}{\partial t} + \mathrm{rot}\frac{1}{ne}\left[\vec{J}\vec{B}\right] = -\mathrm{rot}\left(\frac{1}{\sigma}\vec{J}\right)$$

for the curved magnetic force lines it follows that [6]

$$\frac{\partial \vec{B}}{\partial t}\frac{1}{ne\mu}\left[\vec{B}\nabla\vec{B}\right]\vec{B} = \frac{1}{\sigma\mu}\Delta\vec{B},$$

where $\vec{B}$ — magnetic field induction, $\vec{J}$ — current density, n — magnetized electron concentration, e — elementary electrical charge, σ — plasma conductivity, μ — magnetic constant.

In the framework of a one-dimensional problem the last equation can be written as

$$\frac{\partial B}{\partial t}+\left[\frac{1}{tgF}\frac{2}{r}\frac{1}{ne\mu}B\right]\frac{\partial B}{\partial r}=\frac{1}{\sigma\mu}\Delta\vec{B},\quad B\equiv B_z,$$

where r and z are space coordinates, t is time, and F is angle between spiral curve tangent and radius vector.

Neglecting a diffuse member we have [6]

$$\frac{\partial B}{\partial t}+U\frac{\partial B}{\partial r}\cong 0.$$

Movable layer speed is equal to a convective diffuse velocity

$$U=\frac{1}{tgF}\frac{2}{r}\frac{1}{ne\mu}B.$$

For the model current layer magnetic field becomes zero in the middle of a layer at the distance l. Its Ohmic dissipation speed is equal to the Pounting's vector flow $\frac{lJ^2}{\sigma}=U\frac{B^2}{\mu}$.

Accepting average value of current density square to be equal to $J^2=\frac{l}{2}(\frac{B}{\mu l})$ [7], we get the expression for the movable layer speed: $U=\frac{0.5}{\sigma\mu l}$.

The equality of convective diffusion and Ohmic dissipation speeds determines angle F. Note that in the present work unit system SI is used.

2.2. Plasma Density Determination

Let us suppose that electron concentration and temperature are averaged in space. Magnetized electron concentration n can be calculated using the equality of plasma magnetic moment in the volume confined by current layer and a magnetic moment of the layer current I [8]:

$$\frac{I}{h}=\frac{nkT}{B}$$

where $B\cong 0.5B_o$ [6], $B_o=\frac{\mu I_o N}{h}$, k is Boltzmann constant, T is electron temperature, I_o is antenna coil current, $N=8$ is the number of antenna coil turns, $I\cong I_0N$ is discharge current, and h is axial dimension of the chamber.

Integrating Maxwell electron velocity distribution limited by a spherical pinch-angle we obtain:

$$\frac{n}{n_e}=\frac{0.1(l\omega_B)^2}{2kT/m},\quad (l\omega_B)^2=\frac{3\cdot 10^4\omega_B}{\sqrt{y}},$$

where n_e is plasma electron concentration, ω_B is cyclotron frequency, $y=n_e\cdot 10^{-17}$ is non-dimensional variable.

2.3. Determination of Current Layer Parameters

Equality of magnetized electron flows from plasma to the current layer and back as a result of collisions gives:

$$nU=nv_{ef}2l;\quad U=2v_{ef}l.$$

Effective collision frequency $v_{ef}=v_{ei}+v_a$ includes frequency of single Coulomb scattering at an angle ϑ inside pinch-angle [3]

$$v_{ei}=\left(\frac{\pi/2}{\vartheta}\right)^2 v_{cl}$$

where v_{cl} is frequency of Coulomb collisions at the angle $\pi/2$.

Average value of v_{ei} for the Maxwell electron velocity distribution function at maximal value of $\sin\vartheta=\frac{l\omega_B}{V}$ (here V is electron speed) can be written as $v_{ei}\cong\frac{2y^2}{B^2}$.

Using expression $U=\frac{0.5}{\sigma\mu l}=v_{ef}2l$ it is possible to calculate half-width of the layer $l^4\cong\frac{3\cdot 10^4\omega_B}{\sqrt{y}}$ and the portion of trapped electrons $\frac{n}{n_e}=\frac{3\cdot 10^3\omega_B}{\frac{2kT}{m}\sqrt{y}}$.

Then above mentioned equality of magnetic moments for plasma and layer currents gives:

$$I_0^2 \cong 6 \cdot 10^7 \sqrt{y} \frac{h^2}{N^2} B; \quad I = I_0 N = \frac{B}{\mu} h; \quad B \cong 3 \cdot 10^{-4} \sqrt{y}.$$

Optimal driving frequency can be determined from the equation

$$U = 2r_0 f = 2v_{ef} l. \tag{1}$$

2.4. Model of collisional Mechanism within a Boundary Layer

In the forceless field electric currents flow along the magnetic lines of force [7]

$$\mathrm{rot}\vec{B} = \mu \vec{J} = (\alpha_1 + i\alpha_2)\,\vec{B},$$

where α_1, α_2 are constants. Faraday equation makes it possible to evaluate inducted electric field $\vec{E}$

$$\mathrm{rot}\vec{E} = -\frac{\partial \vec{B}}{\partial t}; \quad \vec{E} = \frac{\vec{J}}{\sigma};$$

Using expression for conductivity $\sigma = \frac{ne^2}{m(v_{ef}+i\omega)}$ we obtain

$$\begin{aligned}
\mathrm{rot}\frac{\vec{J}}{\sigma} &= \frac{(\alpha_1+\alpha_2)^2\,\vec{B}}{\mu\sigma} = -i\vec{B}\omega \\
\alpha_1 &= \sqrt{b}\frac{1}{\sqrt{\gamma + \sqrt{\gamma^2+1}}}; \quad \left(\gamma = \frac{\omega}{v_{ef}}\right) \\
\alpha_2 &= \frac{b}{\alpha_1}; \quad b = \frac{\sigma\omega\mu}{2\,(1+\gamma^2)}.
\end{aligned}$$

Current in the skin sheath has two components shifted by phase. In the Cartesian coordinate system for $\vec{B} = (0, B_y, \sqrt{B^2 - B_y^2})$ it is possible to omit damping of the collisional field [9]

$$B_y = B\sin(\alpha_1 x); \quad B_z = B\cos(\alpha_1 x).$$

While electron moves along x axis across skin sheath, magnetic field vector revolves around this direction and electron is exposed to a non-uniform in space and non-periodic in time electric force. Being involved in this process it can lose phase coherency with the field resulting in stochastic scattering [3]. This mechanism was not taken into consideration in the present work. Collision frequency v_C was determined in the framework of one-dimensional problem [3]

$$v_C \cong \frac{\bar{V}}{4\delta_c}; \quad \delta_c = \left(\frac{\bar{V}}{2\omega\delta_p}\right)^{\frac{1}{3}} \delta_p; \quad 1/\delta_p = \sqrt{\frac{ne^2\mu}{m}},$$

where δ_c is the collisional skin sheath thickness and δ_p is the non-collisional skin sheath thickness.

2.5. Ionization Mechanism and Electron Temperature

Drift time for ions in the gas discharge chamber is much longer than time of current layer movement, therefore ionization processes in all discharge space can be considered as instantaneous. In the equilibrium ionization conditions $\alpha_i n_a n h = n_e \bar{V}_i (1 + \frac{h}{r_0})$, where α_i is ionization coefficient; n_a, n_e, n are concentrations of atoms, plasma electrons, and trapped particles, respectively; h and r_0 are axial and radial dimensions of the chamber, respectively, and $\bar{V}_i$ is the mean ion speed at electron temperature.

The last can be obtained from the following equation

$$\exp\left(\frac{E_i}{kT}\right) = \frac{1.6 \cdot 10^{-14} B h n_a}{(1 + h/r_0)}, \tag{2}$$

where $E_i \approx 16\,\mathrm{eV}$ is the ionization potential for argon.

2.6. Discharge Power and Energy Price of Ions

Magnetic coupling of plasma turn with an antenna coil can be non-transformer. Time variation of plasma turn inductance gives its average resistance

$$R_L \cong \frac{\partial L}{\partial t} = \frac{\partial}{\partial t}\left[\frac{\pi\mu}{h}\left(r_0^2 - r^2\right)\right] \cong \pi\mu U \frac{r_0}{h}$$

where r is a radial coordinate. Resistance component corresponding to power loss W_i in ionization process can be written as

$$R_i = \frac{W_i}{I^2} = \frac{2I_i(16 + 2kT)(1 + h/r_0)}{I^2}$$

where I_i — ion current to a chamber face or to an emission electrode when ICP unit is used together with an ion extraction system. Resistance corresponding to current in a boundary skin sheath

$$R_c = \frac{\pi r_0}{h}\frac{1}{\sigma\delta_c}$$

Resistance of chamber face elements for current circuits was not taken into consideration. It is supposed that discharge area beside emission electrode (when it is present) is short-circuited by this electrode if it is made of electrically conducting material. Note that in the case of a half-sphere gas discharge chamber [10] radial power loss in the boundary skin sheath may be omitted.

Then total discharge power can be written as $W_{\sum} = I^2(R_L + R_i + R_c)$.

Let us denote discharge power divided by the internal surface of the discharge chamber as

$$q_{\sum} = \frac{W_{\sum}}{2\pi r_0^2(1 + h/r_0)} \tag{3}$$

and ion energy price Pr_i as

$$Pr_i = W_{\sum}/I_i \tag{4}$$

where ion current to the emission electrode can be found according to the D. Bohm's formula $I_i = 0.6\pi r_0^2 \cdot en_e(kT/m_i)^{1/2}$ where m_i is the mass of argon ion.

3. COMPARISON OF THEORETICAL RESULTS WITH EXPERIMENTAL DATA

The main ICP discharge parameters in dependence on argon plasma pressure were calculated for a cylindrical gas discharge chamber of 35 cm external diameter surrounded by a cylindrical antenna coil of the same internal diameter for two values of argon ion currents $I_i = 1$ and 5 A.

Dependence of optimal driving frequency on argon plasma pressure determined from formula (1) for both values of argon ion current is presented in Fig. 1.

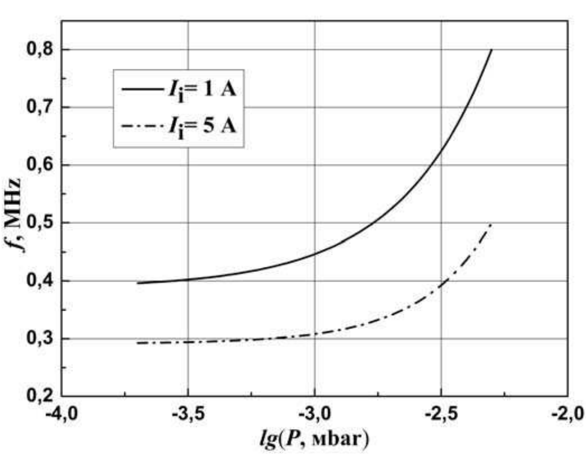

Figure 1: Calculated dependence of the ICP discharge optimal driving frequency on argon plasma pressure.

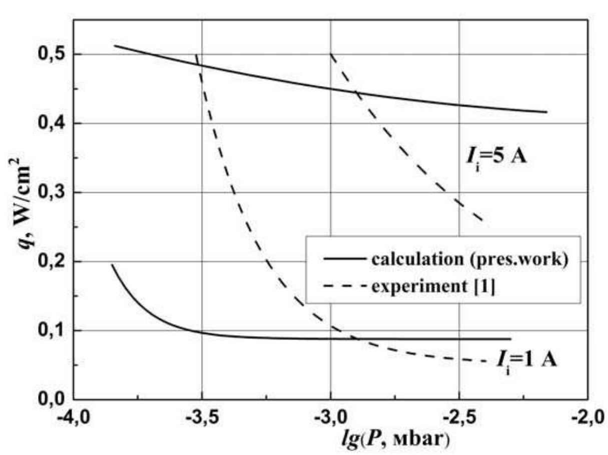

Figure 2: Calculated in the present work (solid lines) and experimental [1] (dashed lines) data on ICP discharge power vs argon plasma pressure.

It was found out that at the upper limit of the considered area of pressures optimal driving frequency for ion current $I_i = 1\,\mathrm{A}$ came close to the experimental value $f \sim 0.75\,\mathrm{MHz}$ [1].

ICP discharge power divided by the internal surface of the gas discharge chamber was calculated using formula (3). Results of these calculations are shown in Fig. 2.

Note that in these calculations the axial and diametral dimensions of the chamber were estimated to be both equal to 35 cm. Results of these calculations are compared here with experimental data [1]. General agreement of this information seems obvious. Note that the agreement can be better if experimental data [1] on plasma pressure could be considered as overvalued. Such peculiarity of the experiment [1] can be quite real because in this work plasma pressure was only estimated.

Energy price of argon ions calculated according to formula (4) is presented in Fig. 3.

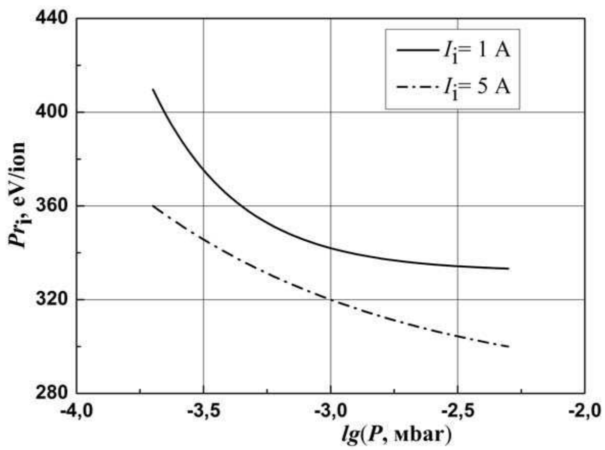

Figure 3: Calculated values of energetic price of argon ions.

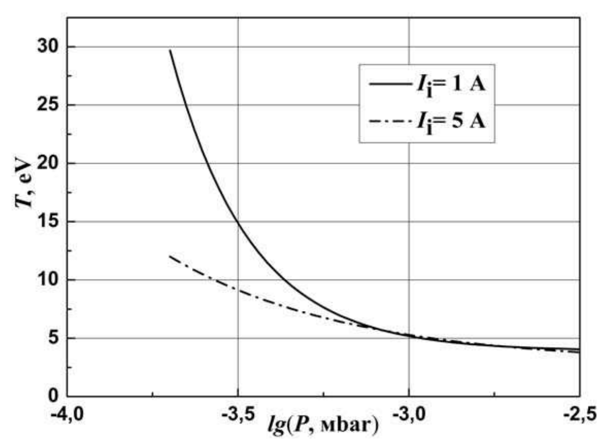

Figure 4: Calculation results for electron temperature of ICP discharge plasma.

Thus obtained results are close to the experimental value $Pr_i = 375\,\mathrm{eV/ion}$ [1] for the gas discharge chamber of 35 cm in external diameter.

Electron temperature calculation data obtained from the Equation (2) are shown in Fig. 4.

It can be seen here that in the case of ion current $I_i = 1\,\mathrm{A}$ electron temperature of argon plasma reached rather high level of $T \sim 30\,\mathrm{eV}$.

Comparison of the present theoretical results with the experiment [1] showed that the ICP discharge model proposed in the present work describes parameters of this discharge close to real life. Therefore it can be used rather confidently to predict properties of the inductive discharges.

4. CONCLUSIONS

- A new model of low pressure ICP discharge based on the concept of movable ionizing current layers has been proposed.
- It has been shown that magnetic coupling of an antenna coil with plasma turn does not always follow transformer logic.
- RF power of the ICP discharge, energy price of its argon ions, optimal driving frequency and electron temperature have been calculated for different argon pressures. Comparison with published experimental data showed that the model satisfactorily describes the main characteristics of an ICP discharge at the selected level of its operational parameters.

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REFERENCES

1. Loeb, H. W., J. Freinsinger, and K. H. Groh, "Feasibility study of large-scale RF-ion thrusters," *Proc. of the 41st IAF Congress*, 231, Dresden, 1990.
2. Godyak, V. A., "Electrical and plasma parameters of ICP with high coupling efficiency," *Plasma Sources Sci. Technol.*, Vol. 20, No. 025004, 2011.
3. Liberman, M. A. and A. J. Lichtenberg, *Principles of Plasma Discharges and Materials Processing*, John Wiley & Sons, Inc., Hoboken, USA, 2005.
4. Godyak, V., R. Piejak, and B. Alexandrovich, "Electrical characteristics and electron heating mechanism of an inductively coupled argon discharge," *Plasma Sources Sci. Technol.*, Vol. 3, 169–176, 1994.
5. Charbet, P. and N. Braithwaite, *Physics of Radio-frequency Plasmas*, Cambridge University Press, 2011.
6. Gordeev, A. V., A. S. Kingsep, and L. I. Rudakov, "Electron magnetohydrodynamics," *Physics Reports*, Vol. 243, No. 5, 215–315, 1994.
7. Priest, E. R. and T. G. Forbes, *Magnetic Reconnection. MHD Theory and Applications*, Cambridge University Press, 2000.
8. Alven, H. and C. G. Falthammar, *Cosmical Electrodynamics*, Clarendon Press, Oxford, UK, 1963.
9. Priest, E. R., *Solar Magneto-hydrodynamics*, Kluwer Academic Publishers, 1982.
10. Leiter, H. J. and D. D. Feili, "RIT15S — A radio frequency ion engine for high specific impulse operation," *37th AIAA/ASME/SAE/ASEE Joint Propulsion Conference*, 2001, Doi: 10.2514/6.2001-3491.