*34th EPS Conference on Plasma Phys. Warsaw, 2 - 6 July 2007 ECA Vol.**31F**, P-4.146 (2007)*

Model of Low Pressure Discharge in Crossed ExH- Fields with Closed Electron Drift

I. Litovko, A. Goncharov*

Institute for Nuclear Research NASU, Kiev, Ukraine

**Institute of Physics NASU, Kiev, Ukraine*

The model of low pressure discharge in cross ExH-fields with closed electron drift had been created and results obtaining from the model are presented. The system of equations is solved numerically by using a finite difference technique and self-consistent solution had been found. The analyze changes in distributions of electron density, potential, temperature, and current density in spatial layer were derived for various plasma parameters.

Introduction

Large class of plasma dynamical devices (plasma accelerators, ion magnetrons, recuperators) use a gas discharge in crossed electric and magnetic fields with closed electron drift. The fundamental concept of this devices are based on application plasma-optical principles of magnetic insulation electrons and equipotentialization magnetic field lines for the control of extra thermal electric fields introduced into the plasma medium that was first described in [1]. As follows from these principles variations of the magnetic field line configuration and the distribution of electric potential enables the formation and control of high current ion beams while maintaining their quasi-neutrality. This makes the application of such devices attractive for the production, formation and manipulation of high current heavy ion beams. The electrostatic plasma lens provides unique and attractive tool for these things. The cylindrical plasma lens is a well-explored device for manipulating and focusing high current, large area, moderate energy, heavy ion beams, where the concern of beam space charge compensation is critical [2-5]. In these investigations it was noted an increasing in the focused ion beam current density for specific low magnetic field strengths. This suggested the possibility of a plasma lens based on the use of permanent magnets. One particularly interesting result of these works was the observation that the plasma lens configuration provides an attractive method for establishing a stable plasma discharge at low pressure. Here we describe the theoretical model of some cylindrical plasma devices and results of numerical simulations of theoretical consideration plasma dynamical discharge characteristics

Theoretical Model of Cylindrical Gas Discharge in Crossed ExH-fields

A common plasmodynamical approach for the analysis of such a system is based on a one dimensional, gas-filled diode space with magnetized electrons and free unmagnetized ions. The design of the diode is shown schematically in Fig. 1 (left). The inner space of the cylindrical cathode with radius R_C and height h serves as target, sputtered by accelerated ions. There are two cylindrical hollow anodes with radius $R_A<R_C$, separated by a distance h. The magnetic field is parallel to the walls of the electrodes. The envelope of the disjoined anode electrodes are forming a virtual cylindrical surface, the potential approximately equals the anode potential according to condition of equipotentialization.

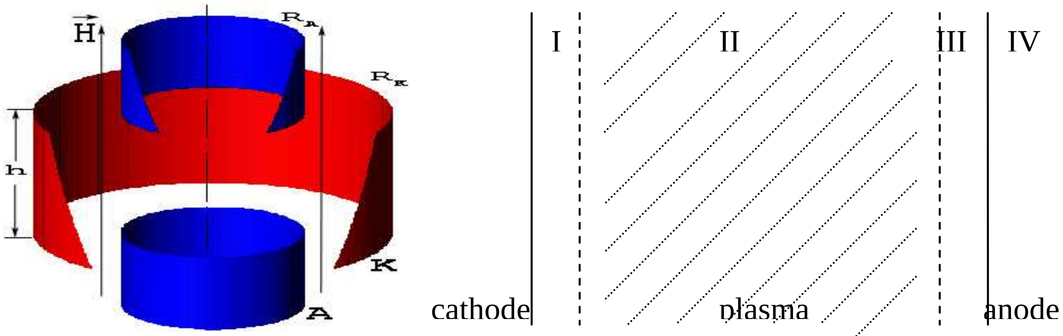


Fig.1 The simplified scheme of cylindrical diode

Typical operating parameters are: pressure of working gas (Ar) is $2\text{-}6\cdot10^{-3}$Torr, the magnetic field is 500-1000Oe, discharge voltage U_d=400-600V, discharge current density j_d=50-100mA/cm^2. Magnetron- type gas discharges in such pressure range are high-currents, thus one can assume the existing of three basic quasi-autonomous regions in the diode-space (as schematically shown in Fig.1 right). According to this approximation we can represent the discharge potential drop as: $U_p = U_{plC} + E_{pl}\cdot\Delta r + U_{plA}$. Here, E_{pl}-is the plasma electric field, Δr is the plasma column dimension, U_{plC}, U_{plA} are cathode and anode drop potential, respectively.

The first zone (I) is the cathode potential drop region U_{plC}, where the main acceleration and ion stream formation occurs. In this region, discharge carrying current is provided by ions with a density j_i and secondary electrons from the cathode $j_e=\gamma\cdot j_i$. Since under similar discharge potentials $\gamma\leq0.1$, one can consider the cathode ion current $j_i = \frac{j_d}{1+\gamma}$ to be approximately equal to the discharge current. Ion current density in the cathode layer can be determined by Longmuir low: $j_d \approx j_i = \frac{1}{9\pi}\sqrt{2\frac{e}{M_i}}\frac{U_{plC}^{3/2}}{d_{plC}^2}$. This is correct when on the plasma boundary the electric field E_{pl} =0. In this case we can use the well-known expression for the ion current density $j_i = 0.4\, en_i\sqrt{\frac{2kT_e}{M_i}}$.Considering $U_{plC}\approx U_d$ and substituting typical values j_d and magnetic field, one can show that the cathode layer size d_{plC} is less than electron

Larmor radius ρ_e. This means that the electrons of the secondary electron–ions emission are not affected by the magnetic field and are accelerated by the potential U_{plC} , and can easily penetrate the second region. Also, we can estimate the plasma ion density, taking into consideration some approximations about the plasma electron temperature.

The second zone (II) is the plasma column zone. Inside this zone, ionization and generation of charge particles takes place. It is a low temperature zone, where the entering high-velocity, as well as the generated low-velocity electrons is magnetized. The ions are free to move to the cathode under influence of a finite E_{pl}. In this region, the one-dimensional equations of two-fluid magnet-hydrodynamics are applicable:

$$\begin{aligned} & j_{epl} = \mu_\perp e n_e \left(E_{pl} - \frac{\nabla (n_e kT_e)}{e n_e} \right) \\ & \nabla j_{epl} = \gamma j_{ic} n_a \sigma_{ee}(v_e) \qquad \nabla j_{ipl} = \gamma j_{ic} n_a \sigma_{ie}(v_e) \\ & \nabla E = 4\pi e (n_i - n_e) \end{aligned} \tag{1}$$

Second equation in (1) describes the generation of electrons and ions in the plasma column due to the cumulative ionization of neutral gas by fast secondary emission electrons only. These electrons do not contribute much to the discharge current, but they are the main ionization factor. The stream of generated slow electrons across the magnetic field in the anode direction is determined by the mobility $\mu_\perp$ in the electric field E_{pl} and diffusion.

The third zone (III) is a narrow region attached to anode that has a size close to the Larmour radius of the electron. The magnetic isolation is eliminated and the electrons are carrying the discharge current. If the anode surface area S_A is so small that $I_d > j_e S_A$, then the anode potential is higher then the plasma potential $U_{plA}>0$ and the anode current of electrons can be described by 3/2-formula. Otherwise, $I_d < j_e S_A$, $U_{plA}<0$ and the electron current into the anode is restricted according to $\sim\exp(-U_{plA}/kT_e)$. The optimal regime provides conditions for which the plasma potential coincides with the anode potential. In this case, all applied U_d is used for the acceleration of the plasma ions at the cathode layer.

Take into account that the main electron energy loss is due to non-elastic collisions and ionization, and thus can change drastically in the plasma layer. If we apply enough common approach considering the average energy of plasma electrons is order by potential drop in plasma column, then $kT_e/e \sim \lambda\varphi$. The first equation of set (1) can be rewritten then in the form:

$$j_{epl} = \mu_\perp e \left(n_e \frac{d\varphi}{dx}(1-\lambda) - \lambda\varphi \frac{dn_e}{dx} \right) \tag{2}$$

So one can get dimensionless set of equations in form:

$$\frac{d^2\varphi^*}{dx^2} = \chi(n^*_i - n^*_e) \qquad \frac{dn^*_i}{dx} = \frac{B}{\sqrt{1-\varphi^*(x)}} \qquad \frac{dj^*}{dx} = \frac{\gamma}{\gamma+1} n_a \sigma_i x_0$$

$$j^*_{epl} = \beta_T \left(n_e^* \frac{d\varphi^*}{dx^*}(1-\lambda) - \lambda\varphi^* \frac{dn_e^*}{dx^*} \right) \qquad (3)$$

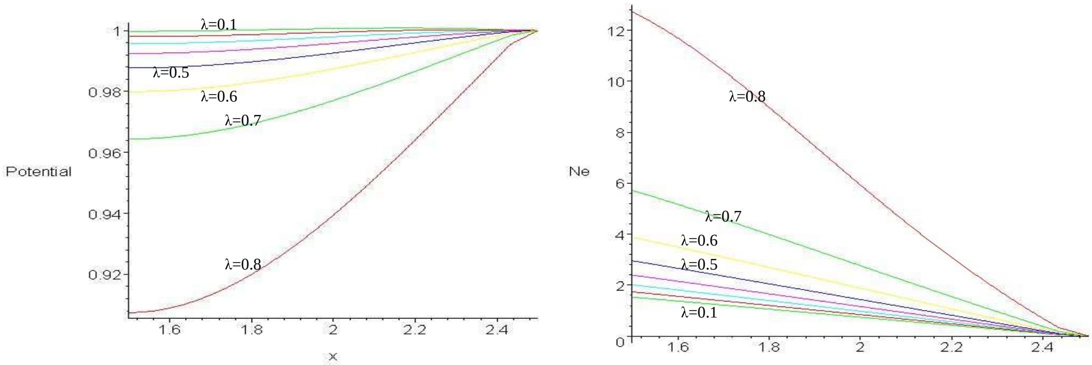
here: $\beta_T = \frac{2.5\mu\varphi_0}{x_0(1+\gamma)}\sqrt{\frac{M_i}{2kT_{e0}}}$; $\chi = \frac{4\pi e n_0 x_0^2}{\varphi_p}$, $B = 0.4\gamma n_a \sigma_i x_0 \sqrt{\frac{kT_e}{e\varphi_p}}$.

Boundary conditions are following:

$$\varphi^*(x_a) = 1 \quad \varphi'(x_k) = 0 \quad n_e^*(x_a) = 0, \quad n_i^*(x_k) = 1, \quad j^* = \frac{\gamma}{\gamma+1} \qquad (4)$$

As scale values for φ, x, j, n_i, n_e was selected next: φ_p – discharge potential, d_0 – plasma column size, j_p - discharge current density, $n_0 = \frac{j_p}{0.4e(1+\gamma)\sqrt{2kT_e/M_i}}$.

By numerically solving equations (1-4) with proper boundary conditions, using an iteration method, we can get self-consistent solutions. For typical parameters shown above the potential drop in the plasma layer can reach 30-50V. The dependence of the potential distribution on λ along the plasma column in arbitrary units is shown in Fig. 2.



a b

Fig. 2 Plasma potential (a) and electron density (b) distribution for various λ

Conclusion

The described physical processes are inherent in many magnetron-type systems. Taking into consideration various modifications of these kinds of systems, this approach can be used to analyze their properties. These devices can be applied both for fine ion cleaning, activation and polishing of substrates directly before deposition, and for sputtering The cylindrical sputtering device described here has good target utilization factor (up to 100%) and a high enough ion current density at the target.

References

[1] A.Morozov and S.Lebedev “Plasmaoptics” in *Reviews of Plasma Physics*, edited by M.Leontovich, (Consultants Bureau, New York, 1975)
[2] A.Goncharov, A.Dobrovolsky, A.Zatuagan and I.Protsenko, IEEE Trans. Plasma Sci., 21(5), 573A (1993)
[3] A.Goncharov, I.Protsenko, G.Yushkov and I.Brown, Appl.Phys. Lett., 75(7), p.911(1999)
[4] A.Goncharov, I.Protsenko , G.Yushkov and I.Brown, IEEE Trans. Plasma Sci., 28(6), 2238 (2000)
[5] A.Goncharov , Rev. Sci. Instr., 73(2),.1004 (2002)