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Theoretical parametric investigation of plasma sustained by traveling electromagnetic wave in coaxial configuration

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ABSTRACT

The electromagnetic wave traveling along a dielectric–gas interface can produce and sustain gas discharge in various geometrical configurations. We propose a parametric study of surface-wave-sustained plasma in coaxial configuration at low pressure based on stationary 1.5D (1D for plasma density and 2D for the wave electromagnetic field components) model. At this configuration the plasma is produced outside a dielectric tube in a low pressure chamber when at the tube axis a metal antenna is arranged. The model gives the phase diagrams and the axial distribution of the plasma density, wave power, wave number, and wave field components, as well as the radial distribution of the wave field components. The dependence of wave and plasma characteristics on the geometry parameters (the plasma radius, the dielectric tube thickness, and the metal antenna radius) and on the dielectric tube permittivity is investigated and shown in this paper. The discharge conditions at which it is possible to sustain plasma by an azimuthally symmetric wave are obtained. Comparison with the cylindrical plasma in corresponding conditions and with experimental data is also presented.

1. Introduction

Gas discharges sustained by traveling electromagnetic surface wave (often called surface-wave-sustained discharges, SWDs) are intensively studied for more than 40 years [1–3]. Usually the plasma is produced inside a dielectric tube filled with the work gas by the electromagnetic wave excited by surfatron [1], surfaguide [4] or Ro-box [5].

New type of SWD was proposed by Räuchle [6] and Kossyi [7] where the plasma is produced outside the dielectric tube in a low pressure chamber when at the tube axis is arranged a metal antenna for electromagnetic wave excitation. It was called coaxial discharge because of the analogy with the coaxial cable with two conductive media (the metal antenna at the axis and the plasma outside the tube) with dielectric between them. Experimental investigations [8,9] of plasma density and electron temperature axial and radial distribution show that this plasma is both radially and axially inhomogeneous. A stationary one-dimensional fluid model is used to calculate the radial profiles of densities and fluxes of positive ions and electrons, the wave field components, and the electron mean energy in He and Ar plasma excited by a coaxial structure [10]. The role of the geometry for axially inhomogeneous plasma sustained in coaxial structure by azimuthally symmetric wave turns out to be very important. It is investigated in Refs. [11–13] by imposing on several parameters defined by the radii of the different media (plasma, dielectric, vacuum, metal).

Independently on the wave launcher and the geometrical configuration of these discharges the mechanism of plasma sustaining by the electromagnetic wave is the following: The wave electric field heats the electrons and they expend the obtained energy for ionization and excitation of the neutral atoms creating and sustaining in this way the discharge. In the same time the plasma becomes a part of the waveguide structure for the wave propagation. This is the main difference with all the other kind of discharges because the dielectric tube here is not just a vessel containing the plasma but together with the plasma is a part of a waveguide structure for propagation of the same wave that sustains the plasma.

The electrons absorb the wave energy thus it decreases along the plasma column. The plasma density decreases, too, and the plasma column is axially inhomogeneous. When the wave power becomes 0 the plasma ends.

This kind of discharges has found already various applications in thin film deposition and UV lamps for sterilizations [14–16]. For dipper understanding the physics and for optimization of their regime of operation and performance additional theoretical investigation is needed. The purpose of this work is to investigate theoretically the dependence of the wave and the plasma characteristics on the geometry parameters (the plasma radius, the dielectric tube thickness, and the metal antenna

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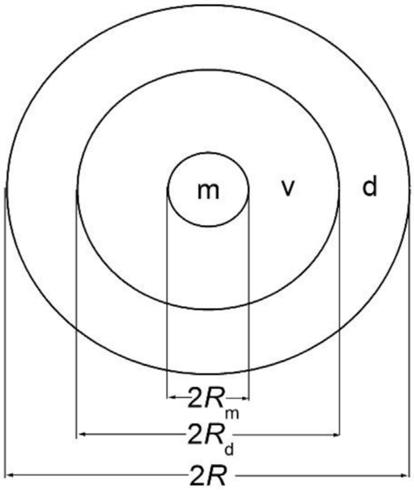

Fig. 1. Cross-section of the waveguide structure.

radius) and on the dielectric tube permittivity. The discharge conditions at which it is possible to sustain plasma by an azimuthally symmetric wave are obtained and presented in the paper.

2. Brief description of the model

The modeling approach is the same as in Ref. [17] but the different waveguide radial structure gives completely different results for the coaxial geometry. Keeping in mind that we have an electromagnetic wave propagating along a waveguide constructed by various media, one of which is plasma sustained self-consistently by the wave itself, we are using the classical approach by solving the Maxwell's equation.

It is characterized by the type (the dielectric permittivity) and the size (the geometry parameters) of the different media. The plasma characteristics (plasma permittivity which is determined by the plasma density n) strongly depend on the above mentioned parameters of the other media in the waveguide. In the experiments the plasma is produced around dielectric tube with metal antenna at its axis and this waveguide is inside a low pressure chamber which walls are far from the waveguide we have studied the simplified configuration metal–vacuum–dielectric–plasma (Fig. 1). The free space between the metal antenna and the dielectric tube is actually open space with air at atmospheric pressure, so its dielectric permittivity can be considered the same as that of the vacuum ($\varepsilon_v = 1$) and we call this free space “vacuum”. The thicknesses of the dielectric and the vacuum are varied and can become 0 so that the configurations metal–vacuum–plasma and metal–dielectric–plasma are also included in the investigation.

The radial size of the different media is characterized by a respective radius: R_m is the radius of the metal rod; R_d is the radius of the dielectric, i.e. the internal radius of the discharge tube; R is the plasma radius, i.e. the outer radius of the dielectric tube. Keeping in mind that the walls of the discharge camera are usually far from the waveguide for the calculations purposes we have assumed that the camera walls are at $r \to \infty$. These geometry characteristics of the waveguide play important role in plasma sustaining and for plasma properties. Thus, the corresponding dimensionless geometry parameters are used in the modeling and they are presented in Table 1. Parameter σ depends on the plasma radius R, the angular frequency ω of the electromagnetic wave and the speed of light c. Parameters γ and η are the radii of the dielectric tube and the metal antenna normalized to the plasma radius R.

A stationary state of plasma produced by electromagnetic wave propagating along the dielectric-plasma interface in axial direction is considered. The plasma is radially inhomogeneous and in our model we have used radially averaged electron number density. This

Table 1
Geometry characteristics and corresponding dimensionless parameters of the waveguide.

Geometry characteristics	Notations and relations	Dimensionless parameters
Plasma radius	R	$\sigma = \omega R/c$
Dielectric tube radius	R_d	$\gamma = R_d/R = 1 - d/R$
Dielectric tube thickness	$d = R - R_d$	
Radius of the metal antenna	R_m	$\eta = R_m/R = \gamma - l/R$
Vacuum space between the metal antenna and the dielectric tube	$l = R_d - R_m$	

approximation corresponds to the spectroscopic measurements of the radially integrated light intensity for the axial plasma density profile determination. It can give correctly the maximum plasma density near the dielectric–plasma interface without its decrease in radial direction. We are suggesting here 1D axial model for the plasma density profile which gives correctly the maximum plasma density distribution in axial direction. The averaged radial plasma density is also used in the calculations of radial distribution of the electromagnetic wave field components by Letout at al. (see Fig. 2 in Ref. [8]). A further improvement of our model requires to take taken into account the radial plasma density distribution, the strong axial and radial plasma inhomogeneity can be taken into account in a complete self-consistent 2D model which is a subject of future investigation.

In our 1.5D model we suppose that the plasma density n, the wave number k and the wave amplitude are slowly varying functions of the axial coordinate z. The plasma is considered as a weakly dissipative medium, i.e. $\nu < \omega$, where ν is the electron–neutral collision frequency for momentum transfer. At this assumption, which is correct at low pressure, the collisions can be ignored in the plasma permittivity and it is used in the form $\varepsilon_p = 1 - \omega_p^2/\omega^2 = 1 - N$, where $\omega_p = (4\pi n e^2/m_e)^{1/2}$ is the plasma frequency with e and m_e the electron charge and mass, respectively. Here $N = n/n_{cutoff}$ is the normalized plasma density with $n_{cutoff} = m_e\omega^2/4\pi e^2$. The plasma sustained by the wave is over-dense, i.e. $N > 1$, $n > n_{cutoff}$ and $\omega_p > \omega$, respectively.

The propagation of the electromagnetic wave along the waveguide structure is described by the Maxwell's equations in cylindrical coordinates r, φ, z. We assume that the electromagnetic wave field components in the different media (p – plasma, d – dielectric, v – vacuum) have the form:

$$E^{p,d,v}_{r,\varphi,z}(r,\varphi,z,t) = Re\left\{F^{p,d,v}_{r,\varphi,z}(r,z)E(z)\exp\left[-i\omega t + im\varphi + i\int_{z_0}^{z} dz' k(z')\right]\right\}, \tag{1}$$

$$B^{p,d,v}_{r,\varphi,z}(r,\varphi,z,t) = Re\left\{G^{p,d,v}_{r,\varphi,z}(r,z)E(z)\exp\left[-i\omega t + im\varphi + i\int_{z_0}^{z} dz' k(z')\right]\right\}.$$

Here $E(z) = E_z(r = R, z)$ is the z-component of the wave electric field at the dielectric–plasma interface. The azimuthal mode number m is included in the expression (1) but only the azimuthally symmetric wave with $m = 0$ is considered in this investigation. Introducing a dimensionless radial variable $\rho = r/R$ from the Maxwell's equations we obtain the wave equation in the zero-order approximation with respect to $(1/k)$ (d/dz)ln$b$, where b is F, G, E, ε or k [17]:

$$\frac{1}{\rho}\frac{\partial}{\partial\rho}\left(\rho\frac{\partial F_z}{\partial\rho}\right) - \left(\frac{m^2}{\rho^2} + x^2 - \sigma^2\varepsilon\right)F_z = 0. \tag{2}$$