Theoretical and experimental investigation of plasma and wave characteristics of coaxial discharges at low pressures

Z. Neichev\textsuperscript{1}, E. Benova\textsuperscript{2}, A. Gamero\textsuperscript{3} and A. Sola\textsuperscript{3}

\textsuperscript{1}Faculty of Physics, Sofia University, 5 James Bourchier Blvd., BG-1164 Sofia, Bulgaria

\textsuperscript{2}Sofia University, 27 Kosta Loulchev Street, BG-1111 Sofia, Bulgaria,

\textsuperscript{3}Departamento de Fisica, Universidad de Còrdoba. Campus Universitario de Rabanales (ed. C2), E-14071 Còrdoba, Spain

E-mail: neichev@deo.uni-sofia.bg

Abstract. The paper discusses a new configuration of the surface-wave sustained plasma – “the coaxial structure”. The coaxial structure is investigated on the base of one-dimensional axial fluid model. That model is adequate enough for low pressure plasma, when the main process for charged particles production is the direct ionization from the ground state and the loss of electrons is due to diffusion to the wall. The role of the geometric factors is evaluated and discussed, varying the discharge conditions in the theoretical model. The main equations of the model – the local dispersion relation and the wave energy balance equation are obtained from Maxwell’s equations with appropriate boundary conditions. The phase diagrams, the radial profiles of the electric field and the axial profiles of dimensionless electron number density, wave number, wave power are obtained at various plasma radii and dielectric tube thickness. The results are compared with those for the typical cylindrical plasma column at similar conditions. For the purpose of modelling at low pressure of a coaxial discharge sustained by a travelling electromagnetic wave, some important characteristics of the propagation of surface waves have been investigated experimentally. The axial profiles of the propagation coefficient and radial profiles of the electric field at different experimental conditions have been obtained and discussed.

1. Introduction

The purpose of this work is to investigate theoretically and experimentally plasma and wave characteristics of coaxial discharges at low pressures. Microwave discharges sustained by traveling electromagnetic waves attracted increasing interest in both fundamental research and technological applications. Due to the broad range of operating conditions these discharges have many fields of use such as plasma-assisted surface treatments, thin film depositions, plasma chemical surface modification, light sources, plasma processing, and many more. Such discharges in planar, cylindrical or spherical geometry are intensively investigated both theoretically and experimentally. Well known configuration researched in the past decades is the cylindrical plasma column. The plasma is produced
inside a dielectric tube. The surface wave propagates along the plasma-dielectric interface. In some cases the dielectric tube is surrounded by a metal cylinder. The cylindrical surface-wave sustained plasma column at low and intermediate pressures is studied in details. A new type of microwave discharge, sustained by travelling wave – a coaxial discharge was proposed recently [1]. The plasma is produced outside the dielectric tube in a low-pressure chamber (Figure 1).

Figure 1. Coaxial discharge configuration

The tube is filled with air at normal pressure and a metal cylinder of small radius is arranged at its axis. The electromagnetic wave propagates along the tube-plasma interface, producing the plasma outside the tube. The plasma in the chamber allows large area treatments and is suitable for plasma technologies. A strong dependence of the plasma density on the gas pressure and the geometric factors is experimentally obtained in the work of Dr. Rauchle [1]. In order to obtain axially homogeneous plasma two microwave sources situated at the ends of the discharge tube were used in his work. He has obtained the radial profiles of the electron density and field components and the axial distribution of the electron density at fixed radial position. Similar coaxial plasma source has been investigated by the group of Prof. Kossyi [2]. In this case the wave has been excited by one magnetron and the plasma is axially inhomogeneous. An increase of the plasma column length with decreasing pressure has been observed there.

To produce devices based on this kind of discharges it is necessary to investigate them both experimentally and theoretically. Their theoretical modeling gives us the opportunity to optimize the plasma characteristics with the gas discharge conditions. In this work we present a theoretical investigation of discharges sustained by 2.45 GHz azimuthally symmetric ($m = 0$) electromagnetic wave propagating along a coaxial structure and compare the wave and plasma characteristics with those of cylindrical columns at similar discharge conditions. We also present and discuss the experimental results we have obtained for the radial distribution of the electric field and the axial distribution of the wave propagation coefficient.

2. Experimental setup
The experimentally investigated system (figure 2) represents two concentric dielectric tubes. The inner tube is filled with air at normal pressure and a metal rod is arranged at its axis. The plasma is produced in the outer tube at low pressure and the working gas is Argon. To produce and sustain the plasma a microwave generator at 2.45 GHz is used. In our investigations we used a vacuum pump to change the pressure and a Piranni device to measure it. We used a phase controller for the microwave interferometry - our experimental technique. This method is based on the relation between the propagation coefficient and the change of the wave phase:

$$\beta = \frac{\Delta \phi}{\Delta z}$$

where $\phi$ is the wave phase and $z$ is the axial coordinate.
Our experimental conditions were input power $P_{in} = 75$ W, reflected power $P_{refl} = 11$ W and gas pressure $p = 1$ Torr.

3. Basic relations and equations

For the theoretical studying the discharge sustained by a coaxial structure at low pressure we apply the approach already used for modelling the cylindrical plasma column sustained by traveling wave at low pressure. We consider the stationary state of a plasma sustained by azimuthally symmetric ($m = 0$) electromagnetic wave ($f = 2.45$ GHz) travelling along the plasma–dielectric interface. We assume that the wave number and the wave amplitude are slowly varying functions of the axial coordinate and the plasma is a weakly dissipative medium. In our model radially averaged plasma density is used and we suppose that it is slowly decreasing from the launcher to the end of the plasma end.

Our model is based on Maxwell’s equations from which we obtain the wave equation, which in cylindrical coordinates ($r, \varphi, z$) takes the form:

$$
\frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial E_z}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 E_z}{\partial \varphi^2} E_z + \frac{\omega^2}{c^2} \varepsilon E_z = 0
$$

(2)

Keeping in mind the abovementioned assumptions we consider the solutions in this form:

$$
E_z(r, \varphi, z, t) = \text{Re} \left[ F_z(r, z) E(z) \exp \left( -i \omega t + i \int_0^z k(z') + im \varphi \right) \right]
$$

(3)

The boundary conditions are the conditions for continuity of the electromagnetic field tangential components at the plasma–dielectric and dielectric–vacuum interfaces and the condition for annulment of the $E_z$-component on the metal screen/rod. From boundary conditions we obtain the local dispersion relation:

$$
\frac{\varepsilon_p K_1(a_p)}{a_p K_0(a_p)} - \frac{\varepsilon_d}{a_d} \frac{\alpha_1 + \frac{\alpha_d}{\alpha_c} \frac{1}{\alpha_5} \alpha_2}{\alpha_3 + \frac{\alpha_d}{\alpha_c} \frac{1}{\alpha_5} \alpha_4} = 0
$$

(4)

The wave energy balance equation is

$$
\frac{dS}{dz} = -Q
$$

(5)

where $S$ is the wave energy flux.
\[ S = \frac{C}{8\pi} \text{Re} \int_0^{2\pi} d\varphi \int_0^{R_1} \hat{r} (E^* \times B) \cdot \hat{z} \]  

(6)

and \( Q \) is the wave power per unit length absorbed by the electrons

\[ Q = \frac{1}{4} \mu_0 E^2 \int_0^{R_1} \hat{r} \left( |F_{\varphi}^p|^2 + |F_{r}^p|^2 + |F_{z}^p|^2 \right) \]  

(7)

At low gas pressure the main process for charged particles production is direct ionization from the ground state and the loss of electrons is due to diffusion to the wall. In this case

\[ Q \propto n_e \]

(8)

By solving together the local dispersion equation and the wave power balance equation we obtain the axial profiles of the normalized plasma density, wave number, wave power and wave field components.

### 4. Results and discussion

The plasma and the wave characteristics depend on the discharge conditions via three geometric factors:

- \( \sigma = \omega R_2 / c \)
- \( \gamma = R_1 / R_2 \)
- \( \eta = R_1 / R_2 \)

Parameter \( \sigma \) represents the dependence on the plasma radius, \( \gamma \) – on dielectric tube thickness and \( \eta \) – on the metal rod radius.

**Figure 3.** Phase diagrams and plasma density axial profiles variations with the plasma radius

We present phase diagrams and plasma density axial profiles variations with the plasma radius on the Figure 3. The metal enclosure is important for the characteristics of cylindrical plasma column when it is close to the discharge tube. At thin metal rod there exists a region of backward wave propagation in the case of coaxial discharge and the plasma density is very low.

**Figure 4.** Phase diagrams and plasma density axial profiles variations with \( \sigma \)
If the metal cylinder is thick the phase diagrams of the coaxial discharge are more similar to those of cylindrical column and we obtain higher plasma densities. The dependence on $\sigma$ is stronger for the coaxial discharge and with increasing the plasma radius the plasma density regularly increases while for the cylindrical column this dependence is not regular (Figure 4).

**Figure 5.** Phase diagrams and plasma density axial profiles variations with $\gamma$

The role of the dielectric tube thickness (parameter $\gamma$) turned out to be very important for cylindrical plasma column sustained by azimuthally symmetric wave. The dependence on the tube thickness in both configurations shows increasing of the plasma density with $\gamma$ (Figure 5). But the plasma density of the coaxial discharge is very low in comparison to the cylindrical column when the plasma radius (parameter $\sigma$) is small.

As we can see, at higher values of the plasma radius the plasma densities of the both configurations are in the same order (Figure 6).

**Figure 6.** Phase diagrams and plasma density axial profiles variations with $\gamma$(higher values of the plasma radius)

The axial profiles of the propagation coefficient and radial profiles of the electric field at different conditions have been obtained experimentally.

On the Figure 7 we present the theoretical calculations for the radial profile of the electric field and on Figure 8 and Figure 9 – the experimental results. The radial profile of the electric field outside the discharge chamber at different axial positions in the case of using a short metal rod in the dielectric tube is presented on the Figure 8. The rod is 3cm long. With the movement to the end of the discharge tube the value of the electric field decreases at fixed radial position. This fact can be expected because of the dissipation of the wave energy in the plasma. The radial profile of the electric field is like a
modified Bessel function $K$, which is known from the theory of surface waves. Our theoretical investigations show the same (Figure 7).

**Figure 7.** Radial profile of the electric field components – theoretical results

The radial profile of the electric field at different axial positions in the case of using both short and long metal rods in the dielectric tube is presented on the Figure 9. The distance between the two rods is 1cm. The curves have the same behavior as in the previous case, but we obtain greater values for the electric field at same radial and axial positions.

We obtained also axial profiles of the propagation coefficient at different gas pressures. These results are shown on the Figure 10. We made our measurements at two different values of the gas pressure:

**Figure 8.** Radial profile of the electric field components – experimental results

**Figure 9.** Radial profile of the electric field components – experimental results

**Figure 10.** Axial profiles of the propagation coefficient
$p = 0.1$ Torr and $p = 1$ Torr. With the movement to the end of the discharge tube the value of the propagation coefficient increases. Such kind of result is expected, because of the decreasing of the plasma density. As we can see with the increasing of the pressure the value of the propagation coefficient at same axial positions slowly increases, too. For $\alpha = 0.717$ rad/cm (at $p = 0.1$ Torr) we obtained that the wavelength is $\lambda = 8.8$ cm, using that $\lambda = 2\pi / \alpha$.

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