Phase diagrams and radial distribution of the electric field components of coaxial discharges with outer dielectric tube at different wave modes

Z Neichev 1, E Benova 2, A Gamero 3 and A Sola 3

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

2 Department for Language Teaching and International Students, Sofia University, 27 Kosta Loulchev Street, BG-1111 Sofia, Bulgaria,

3 Departamento de Física, Universidad de Córdoba E-14071 Córdoba, Spain

benova_phys@deo.uni-sofia.bg

Abstract. The purpose of this work is to investigate phase diagrams and electric field radial distribution of coaxial discharges, sustained by a traveling electromagnetic wave, assuming finite and infinite thickness of the discharge chamber in the model. The calculations are made for azimuthally symmetric and dipolar wave modes. The phase diagrams and the radial profiles of the electric field at various thicknesses of the outer dielectric tube of the chamber and different discharge conditions are obtained. For the purpose of low pressure coaxial plasma modelling, radial profiles of the electric field at different discharge conditions have been investigated experimentally and compared with the theoretical results.

1. Introduction

In this paper we investigate coaxial discharges at low pressures, sustained by traveling electromagnetic waves [1]. This new type of plasma source is very attractive because of an increasing range of their possible technological applications as light sources, especially in automobile industry, also in plasma chemistry, thin film deposition, surface cleaning and material treatments, producing large volume plasma. Typical configuration for such kind of gas discharges is presented in figure 1. The plasma in the coaxial structure is produced between two concentric dielectric tubes. A metal cylinder of small radius is arranged at their axis. The investigated system is at low pressures, so plasma can be considered as a weakly dissipative medium. At this assumption the ratio of the electron-neutral collisions frequency $\nu$ to the wave angular frequency $\omega$ is smaller than unity and can be neglected in the plasma permittivity expression, i.e. $\varepsilon_p = 1 - \frac{\nu^2}{\omega^2}$ ($\omega_p = \left(4\pi e^2 n/m\right)^{1/2}$).
being the plasma frequency). The coaxial structure is investigated on the base of one-dimensional fluid model. The 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 plasma is produced and sustained by a 2.45 GHz surface electromagnetic wave, which propagates along the interface between the plasma and the inner tube. In our previous works we investigate only azimuthally symmetric wave mode. Now we extend our model presenting results for dipolar wave mode also, which can be as much important as the \( m = 0 \) mode. A comparison between the phase diagrams of the different wave modes at various geometric parameters of the system has been made in this paper. The radial profiles of the electric field with and without external dielectric tube are obtained and discussed in order to estimate the influence of the thickness of external tube and the distance between the tubes.

2. Experimental setup

We have obtained experimentally radial profiles of the electric field. The parameters of our experimental discharge chamber are presented in figure 2a and the outlook of the coaxial discharge in figure 2b, respectively. The inner tube is filled with air at normal pressure and a metal rode is arranged at its axis. The plasma is produced between the two tubes at low pressure and the working gas is Argon. To produce and sustain the plasma a microwave generator at 2.45 GHz is used. Our experimental conditions were \( P_{\text{in}} = 75 \text{ W}, P_{\text{refl}} = 11 \text{ W}, p = 1 \text{ Torr} \), where \( P_{\text{in}} \) is the input power, \( P_{\text{refl}} \) is the reflected power and \( p \) is the gas pressure.

The measurements were made with an antenna outside the outer dielectric tube and the results are compared with those, theoretically obtained from our model.

![Coaxial structure diagram](image)

**Figure 2a.** Experimental setup

**Figure 2b.** Outlook of the discharge

3. Basic assumptions 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 [2,3]. We consider the stationary state of a plasma sustained by azimuthally symmetric \( (m = 0) \) or dipolar \( (m = 1) \) electromagnetic wave \( (f = 2.45 \text{ GHz}) \) 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.

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:

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

(1)

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

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

(2)

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 cylinder. From the boundary conditions we obtain the local dispersion relation.

The plasma and the wave characteristics depend on the discharge conditions via some geometric factors. Parameter \(\sigma = \omega R/c\) represents the dependence on the plasma radius \(R\), \(\gamma = R_d/R = 1 + d/R\) – on inner dielectric tube thickness \(d\), \(\eta = R_m/R\) – on the metal cylinder radius \(R_m\), \(\delta_1 = R_1/R\) – on the plasma thickness, \(\delta_2 = R_2/R\) – on the outer dielectric tube thickness (\(R_1\) and \(R_2\) being the inner and outer radii of the outer dielectric tube), \(\Delta \delta = \delta_2 - \delta_1\). If the discharge chamber is large enough so that the wave field decays in radial direction inside the chamber we can assume only the presence of the inner tube of the chamber and the outer one is to infinity. When the two tubes assembling the chamber are close the wave and plasma characteristics depend on \(\delta_1\).

4. Results and discussion

From the local dispersion relation we obtain the phase diagrams. In the case when the distance between the two dielectric tubes is wide enough so that the wave electric field tends to zero inside the discharge chamber we can assume \(\delta_1 \rightarrow \infty\) and the presence of the outer dielectric tube can be neglected in the calculations. We consider that the plasma is sustained outside the dielectric tube. In

\begin{figure}[h]
\centering
\includegraphics[width=0.45\textwidth]{figure3.png}
\caption{Phase diagrams variations with the plasma radius without external dielectric}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.45\textwidth]{figure4.png}
\caption{Phase diagrams variations with the inner dielectric tube thickness without external dielectric}
\end{figure}
that case one can see from figure 3 that with plasma radius (the outer radius of the tube, respectively \( \sigma \)) increasing (at fixed other parameters) the phase diagrams of both \( m = 0 \) and \( m = 1 \) modes are moving down which corresponds to increase of the plasma density. A part of the phase curves above the blue dashed line is in the region of underdense plasma. The phase diagrams of the azimuthally symmetric and the dipolar waves are very close which means that the both modes can produce and sustain overdense plasma with similar density. Although the two wave modes are treated separately in our calculations one can expect a multi-mode regime at the experiment [4,5].

In figure 4 the dependence on the inner tube thickness is presented. When the tube is thin (\( \gamma = 0.9 \)) the phase diagrams of both modes are in the region of underdense plasma at high wave numbers and a region of backward wave propagation appears. A similar behavior is well known when the plasma is sustained inside a cylindrical tube [2]. This is also the reason that all the curves in figure 1 pass through the region of underdense plasma. With increasing of the dielectric tube thickness the phase diagrams are moving down in the region of overdense plasma and the plasma density is also increasing.

The role of the metal cylinder at the axis of the coaxial structure is very important. When this metal rode is thicker (increasing of the parameter \( \eta \) in figure 5) the plasma density is higher which is observed also experimentally [5]. Thus one can change the plasma density only replacing a thin plasma rode at the tube axis with a thicker one.

In all these figures the phase diagrams of the dipolar wave at a given discharge conditions are sharply increasing at small wave numbers. This means that the plasma density is higher when the plasma is sustained by an azimuthally symmetric wave then when it is sustained by dipolar wave. The situation is changed only at higher wave numbers (corresponding to the column end). One can assume that the azimuthally symmetric wave is more efficient for plasma production than the dipolar one but \( m = 1 \) mode does not decay faster and propagates along the plasma together with \( m = 0 \) mode. In some discharge conditions \( m = 1 \) mode becomes even dominant at the plasma end. This investigation shows that there is not any critical value of some of these parameters required for propagation of one of these modes. For comparison, the dipolar wave can propagate along a cylindrical plasma column only at \( \sigma > \sigma_c \) corresponding to \( fR > 2 \text{ GHz cm} \) [6].

The presence of the outer dielectric tube is important when the distance between the two tubes assembling the discharge chamber is small. One can see from figure 6 that the phase curves practically coincide at \( \delta_1 \) from 2 to infinity. At \( \delta_1 = 1.5 \) the plasma density is the same at small wave numbers (close to the wave launcher) but decreases significantly at the column end passing through the region of underdense plasma.

The outer tube thickness effect on the phase diagrams is similar to that of the inner tube thickness: the phase diagrams of both modes pass through the region of underdense plasma at high wave numbers and a region of backward wave propagation appears at small tube thickness \( \Delta \delta = 0.1 \) (compare figure 7 and figure 4).
Assuming the values of the geometric factors calculated for the discharge chamber presented in figure 2 we have obtained the phase diagrams (figure 8) and the radial distribution of the electric field (figure 9) with and without outer dielectric tube. One can see that for both modes the plasma density and the electric field decrease when the outer tube is taken into account. In order to compare the experimental results with those calculated in the model we have to consider the presence of the outer tube so that the modelling is adequate to the real experimental conditions.

In figure 10 the calculated radial distribution of the wave electric field outside the discharge chamber is presented at three axial position corresponding to the experimental conditions. The experimental results are presented in figure 11. The measured and the theoretically obtained electric field has similar behavior: with movement to the end of the discharge tube the value of the electric field decreases at fixed radial position (both figures). This fact can be expected because of the dissipation of the wave energy in the plasma. Our theoretical investigations show that the radial profile
of the electric field is modified Bessel function $K$ (figure 10). The experimentally obtained profiles decrease in radial direction in a similar way (figure 11).

![Figure 10](image1.png)  
**Figure 10.** Calculated radial distribution of the electric field outside the outer dielectric tube corresponding to the experimental discharge conditions

![Figure 11](image2.png)  
**Figure 11.** Measured radial distribution of the electric field outside the outer dielectric tube

5. Conclusion
From the obtained results one can see that the behavior of the profiles for the two wave modes, varying the geometric factors, is similar. Taking into account the external dielectric tube leads to comparable but lower plasma densities than in the case without external tube (or when the discharge chamber is wider). From the phase diagrams we can conclude that there is no dominant wave mode in the system. As it was mentioned by other authors [4,5] and is shown in this paper we may probably have multi-mode regime in the coaxial system, so it is necessary to examine even higher wave modes. Our future goal will be to obtain information about the important modes and the negligible ones as well as the dominant modes in different areas along the plasma column.

6. Acknowledgments
This work was supported by the Bulgarian National Fund for Scientific Research under Grant F-1401/04 and by the Fund for Research of Sofia University under Grant 131/2006. We would like to thank Socrates/Erasmus program and the University of Cordoba, Spain.

References
[1] Benova E and Neichev Z 2002 Axial model of a coaxial discharge sustained by travelling UHF electromagnetic wave *Czechoslovak J. Phys.* **52** D659–65
[2] Zhelyazkov I and Benova E 1989 Modeling of a plasma column produced and sustained by a traveling electromagnetic surface wave *J. Appl. Phys.* **66** 1641–50
[3] Petrova Ts, Benova E, Petrov G and Zhelyazkov I 1999 Self-consistent axial modeling of surface-wave-produced discharges at low and intermediate pressures *Phys. Rev.* **E60** 875–86
[4] Räuchle E 1998 Duo-plasmaline, a surface wave sustained linearly extended discharge *J. Phys. IV France* **8** 99–108
[5] Gritsinin S, Kosyi I, Malykh N, Misakyan M, Temchin S and Bark Y 1999 Preprint No 1 Russian Academy of Science, General Physics Institute, Moscow
[6] Benova E, Ghanashev I and Zhelyazkov I 1991 Theoretical study of a plasma column sustained by an electromagnetic surface wave in the dipolar mode *J. Plasma Phys.* **45** 137–52