The role of a metal screen on the coaxial discharge wave propagation characteristics

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Abstract. The purpose of this work is to investigate theoretically the propagation characteristics of the electromagnetic wave that can produce and sustain plasma in a coaxial structure, as well as the wave field components. We have investigated the coaxial structure which consists of a metal rod in the centre, a dielectric tube, plasma outside the tube and with or without a metal screen. The plasma is both radially and axially inhomogeneous but we consider a radially averaged electron density in describing the plasma and we are presenting here one-dimensional axial model. The basic relation in our model is the local dispersion relation obtained from Maxwell’s equations. Since the plasma is axially inhomogeneous the local dispersion relation gives the dependence between the normalized plasma density and the dimensionless wave number, so called phase diagrams. The radial variations of the normalized wave field components are calculated. The behavior of the phase diagrams and the wave field components is compared in four configurations: metal–vacuum–plasma; metal–vacuum–dielectric–plasma; metal–vacuum–plasma–metal; metal–vacuum–dielectric–plasma–metal.

1. Introduction

The coaxial structure is relatively new type of plasma source, which was proposed recently [1,2]. This new type of plasma source is very attractive because of an increasing range of their possible technological applications as UV lamps [6], surface cleaning, material treatments, plasma sterilization, thin film deposition [7] producing large volume plasma. Typical configuration for such kind of gas discharges is presented in figure 1. The plasma at low pressure in the coaxial structure is produced in a discharge chamber which usually consist of two coaxial dielectric tubes and a metal cylinder of small radius is arranged at their axis. The plasma is both radially and axially inhomogeneous. In some cases the second dielectric tube is replaced by a metal tube. The purpose of this work is to investigate the role of this metal screen on the wave propagation characteristics as well as the influence of the first dielectric tube radius. We studied

Figure 1. Coaxial discharge configuration
theoretically four configurations: (i) metal–vacuum–plasma (mvp); (ii) metal–vacuum–dielectric–plasma (mvdp); (iii) metal–vacuum–plasma–metal (mvpm); (iv) metal–vacuum–dielectric–plasma–metal (mvdpm).

2. Basic assumptions and equations

At low pressures 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. $\varepsilon_p = 1 - \omega_p^2 / \omega^2$ ($\omega_p = \left(4 \pi e^2 n / m\right)^{1/2}$ being the plasma frequency). The plasma is produced and sustained by a surface electromagnetic wave ($\omega / 2 \pi = f = 2.45$ GHz), which propagates along the interface between the plasma and the inner tube. We consider the stationary state of a plasma sustained by azimuthally symmetric ($m = 0$) electromagnetic wave with field components $E = (E_r, 0, E_z)$ and $B = (0, B_\phi, 0)$. We assume that the wave number $k$ and the wave amplitude are slowly varying functions of the axial coordinate and radially averaged plasma density is used:

$$n \equiv \bar{n} = \frac{2}{R^2} \int_0^R r n(r) \, dr.$$

At these assumptions the coaxial structure is investigated on the base of one-dimensional axial fluid model [8]. The fluid model of surface-wave-sustained plasma is applicable at low gas pressures when the main process for electron production is the direct ionization from the ground state and the electron losses are due to the diffusion to the wall. Our model is based on Maxwell’s equations from which we obtain the wave equation. Keeping in mind the abovementioned assumptions we consider the solutions in the form:

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

The solutions of the wave equation give the wave field components amplitude $F_z$ as combinations of Bessel function $J_0$, modified Bessel functions $I_0$, $K_0$, and Hankel function $H_0^{(1)}$ of zero order:

$$F_z^y(a, \rho) = C_1 J_0(a, \rho) + C_2 K_0(a, \rho)$$
$$F_z^d(a, \rho) = C_3 J_0(a, \rho) + C_4 H_0^{(1)}(a, \rho)$$
$$F_z^p(a, \rho) = C_5 J_0(a, \rho) + C_6 K_0(a, \rho)$$

where

$$a_p = (x^2 - \sigma^2 \varepsilon_p)^{1/2}, \quad a_d = (\sigma^2 \varepsilon_d - x^2)^{1/2}, \quad a_v = (x^2 - \sigma^2)^{1/2}, \quad \rho = \frac{r}{R}, \quad x = kR, \quad \sigma = \frac{\omega R}{c}.$$

Similar solutions can be obtained also for the $E_r$ and $B_\phi$ wave field components. The boundary conditions are the conditions for continuity of the electric and magnetic field tangential components $E_z$ and $B_\phi$ at the vacuum–dielectric and dielectric–plasma interfaces and the condition for annulment of the $E_z$–component on the metal cylinders. When the outer metal cylinder does not exist the boundary condition is annulment of the $E_z$–component at infinity. From the boundary conditions we obtain the local dispersion relation:

$$D(\omega, R, \varepsilon_p, \varepsilon_d, \gamma, \eta, \xi, k) = 0,$$

where the geometry of the discharge is included by dimensionless parameters presented in Table 1.

When the plasma is axially homogeneous ($\omega_p = \text{const}$) dispersion relation gives the dependence of the wavelength on the wave frequency, plotted usually in the form $\omega / \omega_h$ versus $kR$ – dispersion diagrams. In our case the dispersion relation (2) is local because of the plasma axial inhomogeneity. It is solved at fixed wave frequency and gives the dependence of the wave number on the plasma frequency (plasma density) usually also plotted as $\omega / \omega_h$ versus $kR$ – the phase diagram.
Table 1.

| Geometric factors | Notations | Parameters |
|-------------------|-----------|------------|
| Plasma radius     | $R$ (outer radius of the dielectric tube) | $\sigma = \omega R/c$ ($c$ – speed of light) |
| Dielectric tube radius | $R_d$ (inner radius of the dielectric tube) | |
| Tube thickness    | $d = R - R_d$ | $\gamma = R_d/R = 1 - d/R$ |
| Radius of the metal rod in the centre | $R_{m1}$ | $\eta = R_{m1}/R$ |
| Radius of the metal screen | $R_{m2}$ | $\xi = R_{m2}/R$ |

3. Results and discussion

Solving the local dispersion relation at fixed $\omega$ we obtain the phase diagrams for the four configurations (figure 2a). The higher plasma density corresponds to the beginning of the plasma column and it is in the region of small wave numbers. With the wave number increasing the plasma density decreases. The cut-off limit for the configurations without dielectric tube corresponds to $(1/2)^{1/2}$ and for configurations with dielectric tube is $1/(1+\varepsilon_d)^{1/2}$. The part of the phase diagram below the $\omega R/\omega_p$ cut-off limit corresponds to overdense plasma and above it – to underdense plasma. One can see from figure 2 that a region of backward wave propagation appears at high wave numbers. In this region the wave cannot sustain plasma and the real end of the plasma column is at the maximum of the phase diagram in the underdense plasma region. When the metal screen is placed the phase diagram moves up, corresponding to a decrease in the plasma density.

Figure 2a. Phase diagrams for the four configurations under investigation

Figure 2b. Phase diagrams at various metal screen radii

Figure 3. Radial distribution of the $E_z$-electric field component for the metal–vacuum–plasma configuration without (a) and with (b) metal screen
We have also obtained that increasing the metal screen radius $R_{m2}$ increases the plasma density (figure 2b) and the best position of the metal screen is at $\xi = 2$ ($R_{m2} = 2R$). Further increasing of this radius does not change significantly the plasma density and the phase diagrams at $\xi = 5$ and $\xi = 10$ practically coincide with that at $\xi = 2$.

The radial distributions of the amplitude of the normalized $E_z$-wave electric field component are presented in figure 3 (without dielectric) and figure 4 (with dielectric) at given discharge conditions. For each phase diagram we have calculated the electric field radial distribution at three $(x, N)$-values presented in figure 2a by different color dots and corresponding to the regions of overdense plasma, underdense plasma and backward wave propagation. For all configurations the electric field amplitude is higher in the overdense plasma region ($x_1$) than in the underdense plasma region ($x_2$). In the region of backward wave propagation ($x_3$) the $E_z$-electric field amplitude is the lowest.

![Graph](image_url)

**Figure 4.** Radial distribution of the $E_z$-electric field component for the metal–vacuum–dielectric–plasma configuration without (a) and with (b) metal screen

### 4. Conclusions

From the obtained results one can see that the coaxial plasma can be used for cleaning and modifying the inner surface of metal tubes. The best conditions and plasma characteristics are obtained at metal screen radius $R_{m2} = 2R$. At smaller metal screen radii the plasma density is lower. Taking into account the existence of the dielectric tube we obtain higher plasma density.

### Acknowledgments

This work was supported by the Bulgarian National Fund for Scientific Research under Grant F 1401/04 and by the Fund for Scientific Research of the University of Sofia under Grant 157/2008.

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Third International Workshop & Summer School on Plasma Physics 2008

Journal of Physics: Conference Series **207** (2010) 012031
doi:10.1088/1742-6596/207/1/012031