OPTIMIZATION OF COAXIAL DISCHARGE OPERATION VARYING THE DIELECTRIC AND METAL ROD CHARACTERISTICS

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1. Introduction

Electromagnetic wave travelling along a dielectric tube can produce plasma outside the tube when there is a metal cylinder at the tube axis [1,2]. Since the plasma is acting as outer conductor, this configuration is called coaxial discharge (Figure 1). The metal cylinder at the tube axis plays very important role for plasma production and plasma density strongly depends on its radius R_m (or parameter $\eta = R_m/R$) [3].

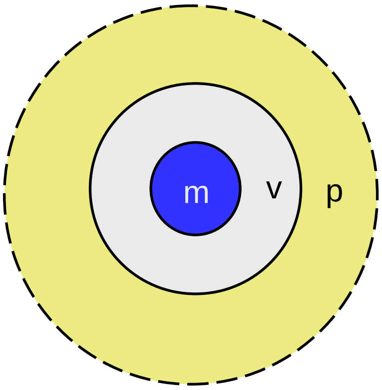


Figure 1. Coaxial configuration (metal–vacuum–plasma)

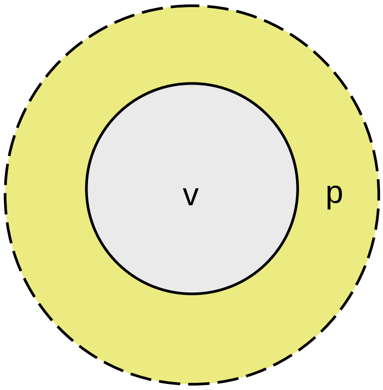


Figure 2 Vacuum–plasma configuration

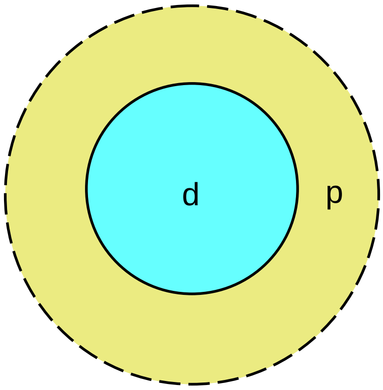


Figure 3. Dielectric–plasma configuration

For comparison, we have studied also structures without any metal cylinder at the axis. The simplest configuration is vacuum–plasma [3] (Figure 2), which is just $1/r$ transform of the cylindrical plasma column of radius R surrounded by vacuum (already widely used and studied in details). Cylindrical plasma column is usually operating in a single wave mode regime because only azimuthally symmetric wave ($m = 0$, m being the azimuthal wave number) can propagate along the column. This is not the case of the coaxial structure, where a multi-mode regime of operation is possible [2]. It has been shown in [3] that the best conditions for sustaining plasma at vacuum–plasma configuration occurs when the wave propagating along the interface is a dipolar one ($m = 1$). Although the dipolar mode is dominant there is not strong decay of the higher modes. Modes with $m > 1$ can propagate and sustain plasma together with the dipolar mode. With increasing the azimuthal wave number (higher modes) the plasma density at the same σ decreases in comparison to the case of dipolar wave but the conditions for plasma sustaining are better than in the case of azimuthally symmetric wave.

Introducing a metal rod at the axis in the case of metal–vacuum–plasma configuration changes drastically the situation [3]. Now the dominant mode is the azimuthally symmetric one. All higher modes can exist and produce plasma but with lower density. In all cases the plasma density increases with increasing the plasma parameter σ but this effect is stronger when the metal rod at the axis is thick one. The metal rod plays a significant role not only for making possible the plasma production at $m = 0$ but also with the very strong effect on the plasma density. The ticker the metal rod at the axis the higher the plasma density [3].

In both configurations the waves in different modes propagate in the same time without strong decay and a multi-mode regime of operation can be expected.

Recently, it has been shown experimentally that plasma can be produced outside a Teflon cylinder without any metal rod at the axis [4]. This corresponds to dielectric–plasma configuration shown in Figure 3.

The purpose of this work is to investigate theoretically the wave modes that can produce and sustain plasma in dielectric–plasma configurations and compare the results with those obtained for the coaxial structure and vacuum–plasma configuration on the base of calculated wave propagation characteristics.

2. Theoretical description

The basic relation in our model is the local dispersion relation obtained from Maxwell's equations. It describes the wave propagation along the waveguide structure. Its form is quite complicated and depends on the configuration and azimuthal wave modes but generally can be written in the form:

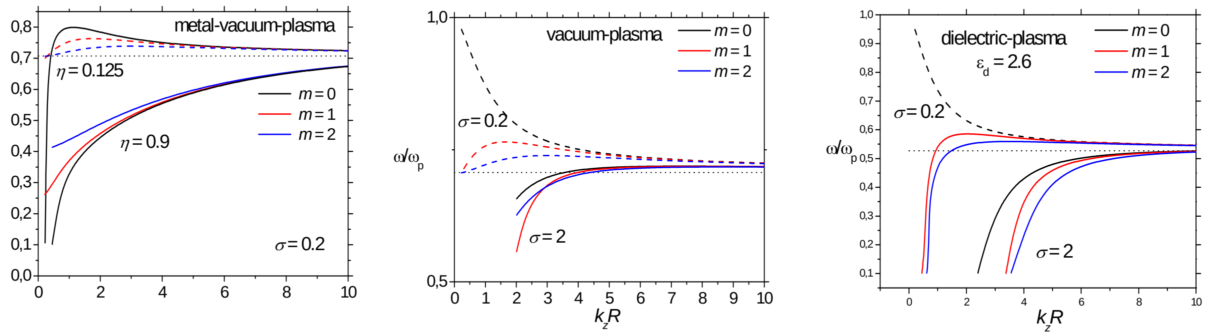
$$\mathrm{D}(m, \omega, R, \varepsilon_{\mathrm{d}}, \eta, k_z, \omega_{\mathrm{p}}) = 0. \quad (1)$$

Since the plasma is axially inhomogeneous the local dispersion relation gives the dependence between the normalized plasma density $N = n/n_{\mathrm{cutoff}}$ ($n_{\mathrm{cutoff}} = m\omega^2/4\pi e^2$, m and e being the usual notations for electron mass and charge) via plasma frequency ω_{p} and the dimensionless wave number $x = k_z R$, at fixed wave frequency ω, so called phase diagrams. From the behaviour of the phase diagrams at given discharge configurations one can obtain information about the ability of the different wave modes to sustain plasma and about the plasma density. Varying the dielectric permittivity, dielectric and metal rod thicknesses in the configurations included in this investigation one can find optimum plasma density and electric field distributions for a given application. Thus we suggest a very simple way for optimization of the plasma source operation and obtaining optimum plasma characteristics by appropriate choice of the discharge geometry.

3. Results and discussion

The local dispersion equation (1) is solved numerically for the three configurations shown in Figutes 1–3 at various wave modes, values of plasma parameters σ and η, and dielectric permittivity ε_d.

Figure 4b,c shows the phase diagrams for small plasma parameter σ = 0.2 and for quite big value σ = 2, which at wave frequency of 2.45 GHz corresponds to about 2 cm plasma radius. For vacuum–plasma and dielectric–plasma there exists only a region of backward wave propagation in the phase diagram (dashed black line) at σ = 0.2 when the wave is azimuthally symmetric one (m = 0). We assume that such a wave cannot produce plasma. At the same small value of σ if even a very thin metal rod is arranged at the axis (η = 0.125) the forward wave propagation region exists in the phase diagram and plasma with high density can be produced by the azimuthally symmetric wave (Figure 4a).



(a) (b) (c)

Figure 4. Phase diagrams for the three configurations: metal–vacuum–plasma (a), vacuum–plasma (b) and dielectric–plasma (c) for azimuthally symmetric (m = 0), dipolar (m = 1) and quadrupolar (m = 2) waves

If the metal rod is thick (η = 0.9) the situation is even better and plasma density is higher at the same wave number (phase diagram is shifted down). The dominant mode producing plasma with highest density is the azimuthally symmetric one but the higher modes can also propagate and produce plasma although with lower density. Compare the three graphs one can see that the higher wave modes at small σ are not appropriate for sustaining plasma at metal–vacuum–plasma and vacuum–plasma configurations (small region of forward wave propagation with very low plasma density) while plasma with high density can be produced at dielectric–plasma configuration. The phase diagrams corresponding to m = 1 and

m = 2 at this configuration are very close and a multi-mode regime of operation expects with comparable plasma densities produced by these two modes.

At $\sigma = 2$ all wave modes have phase diagrams corresponding to high plasma density. At vacuum–plasma configuration the dominant mode at this condition is the dipolar one (m = 1) while at metal–vacuum–plasma the azimuthally symmetric mode (m = 0) is always dominant. At dielectric–plasma configuration the three modes have very close phase diagrams and there is not dominant mode but strong multi-mode regime instead.

Figure 5 shows the phase diagrams of azimuthally symmetric wave at various σ. At small σ only backward wave propagation region exists while with σ increasing a region of forward wave appears. As it has been shown in [3] for vacuum–plasma (Figure 5a) there exists a "critical" value of the plasma parameter, $\sigma_{cr} \approx 1.56$ which divides these two groups of phase curves. It corresponds to $(fR)_{cr} \approx 7.45$ GHz cm which means that one can expect to produce plasma in such configuration with high enough wave frequency and plasma radius. We assume that at $\sigma < \sigma_{cr}$ the wave cannot sustain plasma at this geometry. For dielectric–plasma (Figure 5b) the situation is similar but the value of σ_{cr} depends on the dielectric permittivity ε_d. For Teflon (ε_d = 2.6) σ_{cr} is slightly lower than 1 while at bigger ε_d it is smaller.

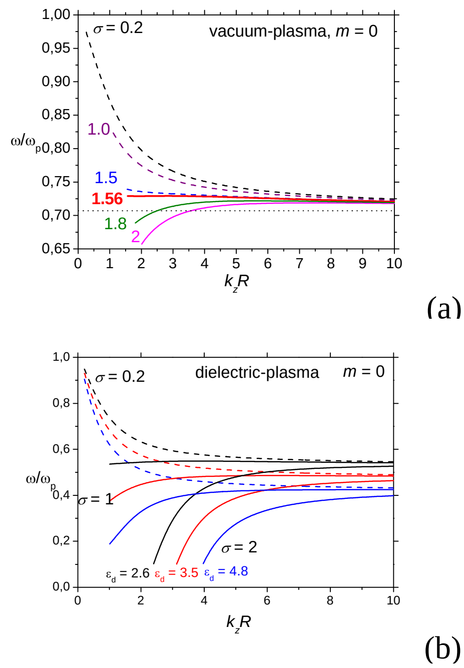


Figure 5. Phase diagrams for azimuthally symmetric wave at various σ

4. Acknowledgements

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