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WAVE PROPAGATION CHARACTERISTICS OF COAXIAL DISCHARGE SUSTAINED BY TRAVELLING ELECTROMAGNETIC WAVE

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Introduction

Microwave discharges sustained by travelling electromagnetic waves are intensively investigated in the past decades both theoretically and experimentally. The cylindrical surface-wave sustained plasma column is studied in detail. The coaxial structure is relatively new type of plasma source, which was proposed recently [1,2]. In the coaxial structure the dielectric tube is filled with air at normal pressure and the plasma is produced outside the dielectric tube in a low-pressure chamber. A metal rod is arranged at the dielectric tube axis.

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 shown in figure 1. We have investigated the coaxial structure which consists of a metal rod in the centre, a dielectric tube, plasma outside the tube and a metal screen. The plasma is both radially and axially inhomogeneous.

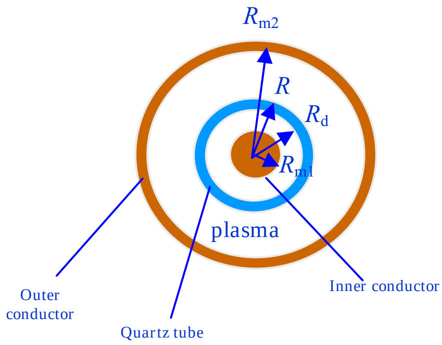

Fig. 1.Coaxial discharge structure

Basic assumptions and relations in the model

In our modelling we consider the stationary state of a plasma at low pressure sustained by azimuthally symmetric EM wave ($\omega/2\pi$ =2.45 GHz) travelling along the plasma–dielectric interface. A radially averaged electron number density is used and we also assume that the plasma density, the wave number k_z and the wave amplitude are slowly varying functions of the axial coordinate. The plasma is considered as a weakly dissipative medium and the collision term in the plasma permittivity is neglected.

The basic relation in our model is the local dispersion relation obtained from Maxwell's equations [3]. Since the plasma is axially inhomogeneous the local dispersion relation gives the dependence between the normalized plasma density N ($\omega/\omega_p = 1/\sqrt{N}$) and the dimensionless wave number k_zR, so called phase diagrams. The radial variations of the wave field components are also calculated. From the behavior of the phase diagrams and the wave field components at different discharge conditions one can obtain information about the ability of the wave to sustain plasma and about the plasma density.

The wave and plasma characteristics, as well as the radial variations of the wave field components strongly depend on the discharge conditions and the geometry of the coaxial structure. The geometric parameters used in the model are presented in Table bellow:

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

Results and discussion

The phase diagrams and the E_z–wave field components are presented in figure 2 at various dielectric tube thicknesses. The black curves correspond to the simplest configuration metal–vacuum–plasma–metal when the existence of the dielectric tube is neglected. In that case the line corresponding to the resonance values of the plasma density $n_{\mathrm{res}} = 1 + \varepsilon_{\mathrm{d}}$ (ε_{d} is the dielectric tube permittivity) is at $1/\sqrt{2}$ since $\varepsilon_{\mathrm{d}} = \gamma = 1$. Without the dielectric tube the E_z–component of the wave electric field has the typical surface wave behavior with a maximum at the interface. The presence of the tube with dielectric permittivity $\varepsilon_{\mathrm{d}} = 3.8$ changes the resonance value to $1/\sqrt{4.8}$ and the phase diagrams move down with increasing the tube thickness (parameter γ). For small values of the wave number k_z the phase diagrams are bellow the line corresponding to n_{res} which means that the plasma is overdense one. The part of the phase diagrams above this line corresponds to underdense plasma which appears at the column end where the wave number is higher. When the dielectric tube is taken into account there is a maximum in the phase diagrams after which a region of backward wave propagation appears. In fact, the plasma exists only in the region of the forward wave propagation and the real end of the plasma column is at the maximum of the phase curve which is in the region of underdense plasma. The maximum of the E_z electric field is not always at the plasma–dielectric interface but depending on the tube thickness and the position on the phase curve it can also be at the dielectric–vacuum interface going to 0 at the two metal surfaces.

Figure 3 shows strong dependence on the metal rod thickness. One can see that at small values of η (thin metal rod) the phase diagrams are crossing the $1/\sqrt{1+\varepsilon_{\mathrm{d}}}$ line. They are passing through the region above this line where $n_e < n_{res}$ (underdense plasma) and a region of backward wave propagation appears after the maximum of the curve. With increasing the metal rod thickness the phase diagrams move down, which corresponds to increasing of the plasma density. For very thick metal rods (when the vacuum space between the rod and the dielectric tube is very narrow) the calculations show that there is no more a backward wave propagation and underdense plasma region.

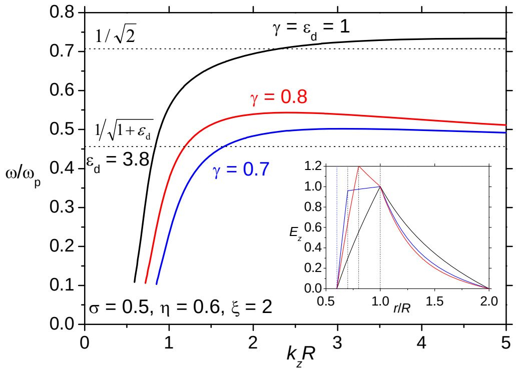

Fig. 2. Phase diagrams and radial distribution of the E_z –wave field component at various tube thicknesses

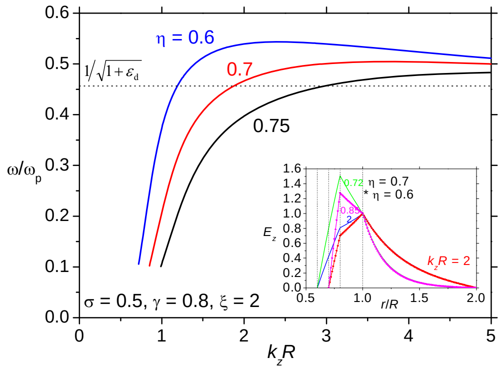

Fig. 3. Phase diagrams and radial distribution of the E_z –wave field component various metal rod thicknesses

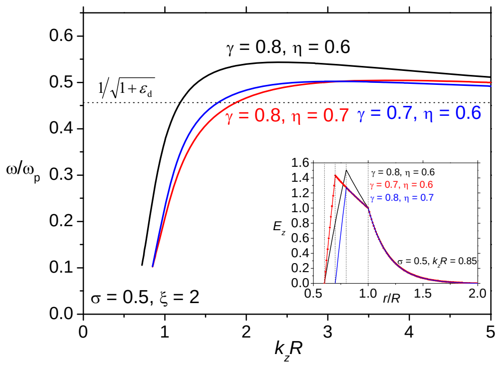

Fig. 4. Phase diagrams and radial distribution of the E_z –wave field components at various γ and η

For plasma and wave characteristics is important to know not only the thickness of the metal rod and dielectric tube but also the distance between them. The black phase diagram in figure 4 is for wider space between them ($\gamma = 0.8$, $\eta = 0.6$). At the same value of γ (the same radius of the tube) but thicker metal rod ($\eta = 0.7$) the space between the rod and tube is smaller and the plasma density is much higher (red curve). Keeping the same distance between the metal rod and the dielectric tube but with thinner rod and smaller tube radius ($\gamma = 0.7$, $\eta = 0.6$) we obtain a phase diagram close to the previous (blue curve). One can see that the conditions for plasma creating are the best at thicker metal rod and small distance between it and the dielectric tube. In that case the plasma density is higher.

In this configuration the plasma is sustained outside the dielectric tube which is surrounded by a metal tube. The main reason for this is the possibility to use the plasma for treating and cleaning the internal surface of the metal tubes. In the same time the metal tube becomes a part of the coaxial structure and can significantly change the plasma properties. The ratio of the metal tube radius and the plasma radius (parameter ξ) is used to investigate the influence of the metal tube on the plasma characteristics.

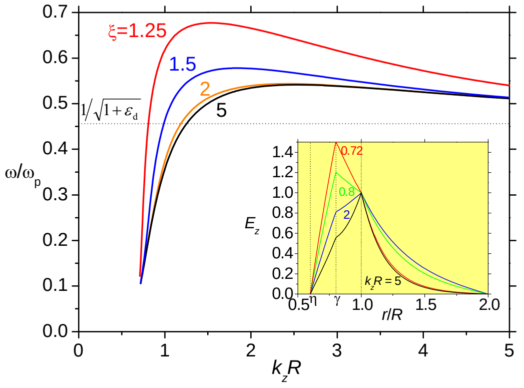

Fig. 5a. Phase diagrams and radial distribution of the E_z–wave components at σ = 0.5, γ = 0.8, η = 0.6 and various metal tube radii

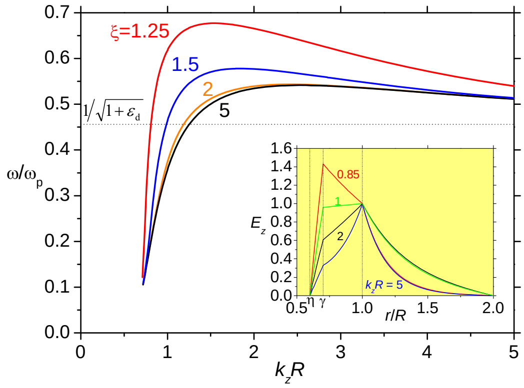

Fig. 5b. Phase diagrams and radial distribution of the E_z –wave components at σ = 0.5, γ = 0.7, η = 0.6 and various metal tube radii

One can see (figure 5) that when the metal tube is very close to the dielectric one (ξ = 1.25), in the space between them is produced plasma which is underdense in a wide wave number interval. The maximum of the phase diagram (the real end of the plasma) is also at small k_z. Only for very small values of k_z the region of overdense plasma exists. These conditions are not appropriate for sustaining plasma and the plasma properties are not the best for the applications. With increasing the metal tube radius the phase diagrams are moving down, their maximum is shifted to the bigger wave numbers and the plasma density is increasing. One can see that practically there is not difference between the phase diagrams at ξ = 2 and ξ = 5. This means that when the metal tube is far from the dielectric tube in a distance equal to the plasma radius we can assume that it is at infinity and increasing this distance does not change the plasma characteristics anymore.

Acknowledgments

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