Effect of geometry parameters on wave and plasma characteristics of coaxial microwave discharge

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Electromagnetic wave can produce plasma outside the dielectric tube when there is a metal cylinder at the tube axis [1, 2]. We named this configuration coaxial discharge. The possible configurations depend on the radial distribution of different materials like metal, vacuum, dielectric and plasma. We have studied metal–vacuum–plasma configuration.
The basic relations in our model are the local dispersion relation and wave energy balance equation obtained from Maxwell's equations [4]. The plasma is axially inhomogeneous and the dispersion relation gives the so called phase diagrams – dependence between the normalized plasma density and the dimensionless wave number. Axial profiles of plasma density and wave power are presented, too. From the behaviour of the diagrams at different discharge configurations we can obtain information about the ability of the wave to sustain the plasma and about the wave and plasma characteristics.

1. Introduction

Electromagnetic wave travelling along a dielectric tube can produce plasma inside the tube which is the typical cylindrical plasma column of surface-wave-sustained discharges. The cylindrical plasma column is studied in details and it is well known that the plasma inside the tube is produced by one wave mode only, azimuthally symmetric one (m = 0) in most of the cases. In some particular cases it is possible to produce plasma column by travelling dipolar wave (m = 1) [3]. In that case the azimuthally symmetric wave decays very fast and again only one wave mode is propagating. One of the main characteristics of the cylindrical plasma column sustained by travelling wave is the single mode regime of operation.

Electromagnetic wave can produce plasma also outside the dielectric tube when there is a metal cylinder at the tube axis. Since the plasma is acting as outer conductor, this configuration is named coaxial discharge (fig. 1). When the plasma is sustained by traveling electromagnetic wave in a coaxial structure the single mode regime is not proved.

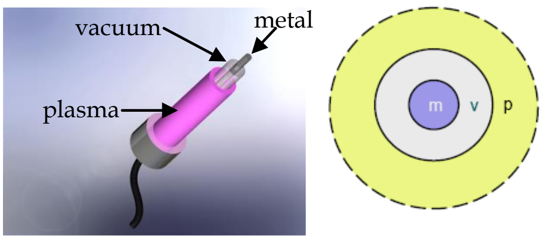

Fig. 1. Metal–vacuum–plasma coaxial discharge structure

The possible exciting of dipolar and higher modes together with the azimuthally symmetric one is experimentally observed in [2].

The purpose of this work is to investigate theoretically the azimuthally symmetric wave that can produce and sustain plasma in the coaxial structure and plasma and wave characteristics. For simplicity, we have investigated a coaxial structure which consists of a metal rod in the centre, vacuum and plasma.

2. Basic assumptions and relations in the model

In our modelling we consider the stationary state of a plasma at low pressure sustained by electromagnetic (EM) wave ($\omega/2\pi$ = 2.45 GHz) travelling along the plasma–vacuum interface. The wave electric field heats the electrons so they absorb the wave energy. As a result the wave energy decreases along the plasma column. The plasma density decreases too and the plasma column is axially inhomogeneous. We assume that the plasma density, the wave number k_z and the wave amplitude are slowly varying functions of the axial coordinate. The investigation is based on one-dimensional axial fluid model and we use radially averaged electron number density. The fluid model is applicable at low pressure when the main process of plasma creation is direct ionization from the ground state and the losses of the charged particles are due to their diffusion. The plasma is considered as a weakly dissipative medium and the collision term in the plasma permittivity can be neglected, i.e. we use the plasma permittivity in the form:

$$\varepsilon_p = 1 - (\omega_p^2/\omega^2) \qquad (1)$$

where

$$\omega_p^2 = \sqrt{4\pi e^2 n / m_e} \qquad (2)$$

is the plasma frequency, n is the plasma density and e, m_e – electron charge and mass.

The modelling approach in this paper is similar to the one used for coaxial discharge sustained by azimuthally symmetric (m = 0) TM wave [4] where the wave electromagnetic field possesses only three components **E** = (E_r, 0, E_z), **B** = (0, B_φ, 0). Our model is based on Maxwell's equations from which we obtain the wave equation. In cylindrical coordinates (r, φ, z) it takes the form:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial}{\partial r}E_z\right)+\frac{\partial^2}{\partial z^2}E_z+\frac{\omega^2}{c^2}\varepsilon E_z=0 \qquad (3)$$

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

$$E_z(r,\varphi,z,t)=\mathrm{Re}\left[F_z(r,z)E(z)\exp\left(-i\omega t+\int_0^z dz'k(z')+il\varphi\right)\right] \qquad (4)$$

The amplitude function F_z is presented as a combination of Bessel or modified Bessel functions in the different media. Similar equations and solutions can be obtained for the other EM field components. The boundary conditions are the conditions for continuity of the electromagnetic field tangential components at the plasma–vacuum interface and the condition for annulment of the E_z – component on the metal rod. From boundary conditions we obtain the local dispersion relation symbolically written down as

$$D(\omega, k_z, R, \varepsilon_p, \eta) = 0 \qquad (5)$$

Here R is the plasma radius and $\eta = R_m / R$, where R_m is the metal rod radius. Since the plasma is axially inhomogeneous the local dispersion relation gives the dependence between the normalized plasma density N ($\omega/\omega_p = 1/\sqrt{N}$, $N = n/n_{cut\,off}$, $n_{cut\,off} = m\omega^2/4\pi e^2$) and the dimensionless wave number k_zR, so called phase diagrams.

From Poynting's theorem one gets other important equation which reads

$$\frac{dS}{dz} = -Q \qquad (6)$$

Where S is the wave energy flux and Q is the wave power per unit column length absorbed by the electrons. Wave energy is presented as a sum of the axial components of Poynting's vector averaged over wave period $2\pi/\omega$ and integrated over the plane normal to the plasma column, from the axis to infinity, at given axial position ζ:

$$S = 2\pi\int_\eta^1 rS_z^v dr + \int_1^\infty rS_z^p dr \qquad (7)$$

Here p and v denote plasma and vacuum and

$$S_z = \frac{1}{\mu_0}\left(E_r^* B_\varphi - E_\varphi^* B_r\right). \qquad (8)$$

The absorbed power Q should be proportional to the radially averaged electron density which is related with normalized plasma density N. Absorbed power take the form:

$$Q = CN \qquad (9)$$

where C is proportionality coefficient.

Solving the wave energy balance equation (6) together with Eq. (9) we obtain the normalized axial distribution of the normalized plasma density $N(\zeta)$ where $\zeta = \dfrac{z\nu}{R\omega}$.

3. Results and discussion

Investigation is focused on the role of plasma parameter σ ($\sigma = \omega R/c$, ω – external field frequency, R – plasma radius, c – speed of light) and geometrical factor η ($\eta = R_m/R$, R_m – radius of the antenna) in sustaining of plasma and their effect on the axial distribution of normalized plasma density. Antenna thickness and plasma radius are varying and investigated cases are presented in Table. 1.

Table. 1. Table of studied geometrical configurations

σ \ η		0,125	0,250	0,500	0,750	0,875	
0,2567	R_p =	5,00	5,00	5,00	5,00	5,00	[mm]
	R_m =	0,63	1,25	2,50	3,75	4,38	[mm]
0,5135	R_p =	10,00	10,00	10,00	10,00	10,00	[mm]
	R_m =	1,25	2,50	5,00	7,50	8,75	[mm]
0,7702	R_p =	15,00	15,00	15,00	15,00	15,00	[mm]
	R_m =	1,88	3,75	7,50	11,25	13,13	[mm]
1,0270	R_p =	20,00	20,00	20,00	20,00	20,00	[mm]
	R_m =	2,50	5,00	10,00	15,00	17,50	[mm]
1,2837	R_p =	25,00	25,00	25,00	25,00	25,00	[mm]
	R_m =	3,13	6,25	12,50	18,75	21,88	[mm]
1,5404	R_p =	30,00	30,00	30,00	30,00	30,00	[mm]
	R_m =	3,75	7,50	15,00	22,50	26,25	[mm]
1,7972	R_p =	35,00	35,00	35,00	35,00	35,00	[mm]
	R_m =	4,38	8,75	17,50	26,25	30,63	[mm]
2,0539	R_p =	40,00	40,00	40,00	40,00	40,00	[mm]
	R_m =	5,00	10,00	20,00	30,00	35,00	[mm]
2,3107	R_p =	45,00	45,00	45,00	45,00	45,00	[mm]
	R_m =	5,63	11,25	22,50	33,75	39,38	[mm]

From the behaviours of the phase diagrams at different discharge conditions one can obtain information about the ability of the wave to sustain plasma and about the plasma density. When N decreases with increasing of k_zR, till going to maximum of the phase diagram, we observe forward wave propagation. When N increase with increasing of wave number (behind maximum of phase diagram) – backward wave propagation region. We assume that backward wave cannot sustain plasma and maximum of the phase diagram correspond to the end of the plasma column.

Solving the dispersion relation for azimuthally symmetric wave, 5 mm plasma radius and various antenna thicknesses we obtain the phase diagrams for given configurations (fig. 2).

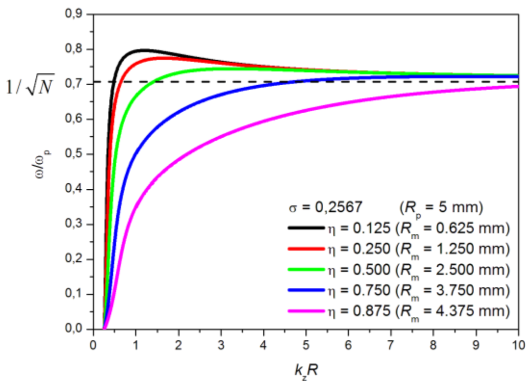

Fig. 2. Phase diagrams for 5 mm plasma radius and various antenna thicknesses

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 phase diagram goes over $\omega/\omega_p = 0.707$, which is at plasma densities $n < 2n_{cutoff}$.

From the given phase diagrams one can see that in case of thin antenna ($R_m < R_p/2$) is observed backward wave propagation region. For very thick metal rods (when the vacuum space between the rod and the plasma is very narrow) the calculations show that there is no more a backward wave propagation.

For plasma and wave characteristics is important to know not only the thickness of the metal rod and plasma radius but also the distance between them. Keeping plasma radius (plasma parameter σ) constant and increasing antenna thickness (fig. 2) one can see that thicker antenna leads to plasma column with higher dimensionless plasma density. Confirmation of that conclusion could be found at the axial distribution of N (fig. 3). One can see that thicker metal antenna leads to plasma column with higher plasma density for given dimensionless axial coordinate ζ.

Decreasing thickness of the vacuum layer ($R - R_m$) dimensionless plasma density N decreases, too. At the beginning of column, plasma density is maximal and decreases till the end of column. The thickest antenna leads to plasma density which is more than one order higher than plasma density produced by the thinnest antenna.

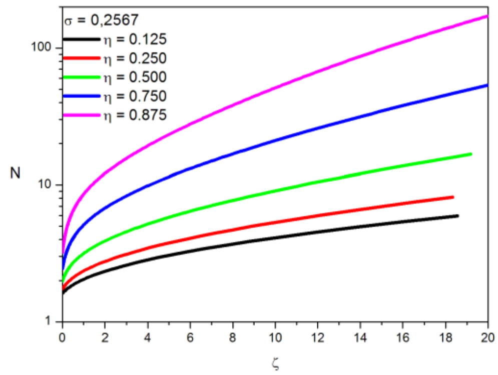

Fig. 3. Axial distribution of dimensionless plasma density for 5 mm plasma radius and various antenna thicknesses

The higher plasma density is produced with higher wave power which can be seen form fig. 4. More than one order higher plasma density is produced with more than fifteen times higher wave power at the beginning of the column.

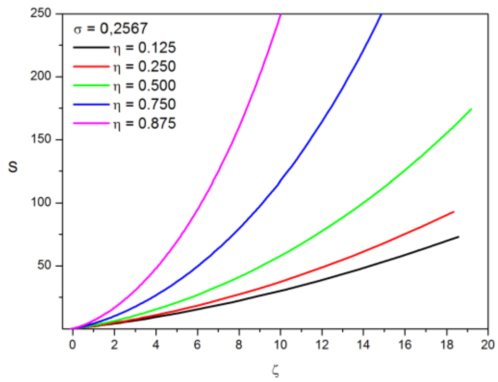

Fig. 4. Axial distribution of wave power flux for 5 mm plasma radius and various antenna thicknesses

Keeping antenna thickness – plasma radius ratio constant ($\eta = R_m/R = 0.125$, fig. 5) and increasing plasma radius R (5 mm – black dashed line, 25 mm – red dashed line, 45 mm – blue dashed line) one can see that bigger plasma radius leads to significant change of phase diagrams behaviour. Backward wave propagation region is not observed.

In case of higher ratio between antenna thickness and plasma radius ($\eta = R_m/R = 0.875$, fig. 5) backward wave propagation is not observed in the phase diagrams for all studied radii (5 mm – black solid line, 25 mm – red solid line, 45 mm – blue solid line). Phase diagram for higher plasma radius is below the phase diagram for lower plasma radius in both studied cases for geometry parameter η.

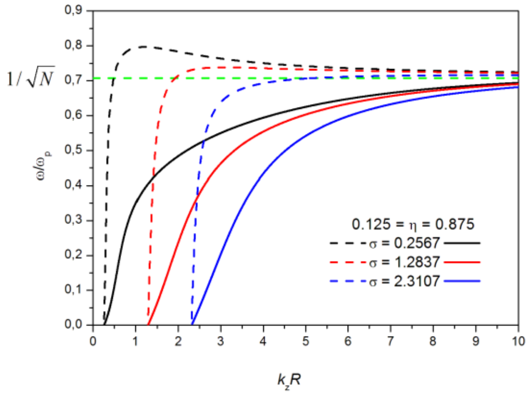

Fig. 5. Phase diagrams for thin antenna (dashed lines) and thick antenna (solid lines) at various plasma radii

Axial profiles of dimensionless plasma densities (fig. 6) and wave power fluxes (fig. 7) of studied previously configurations are presented, too.

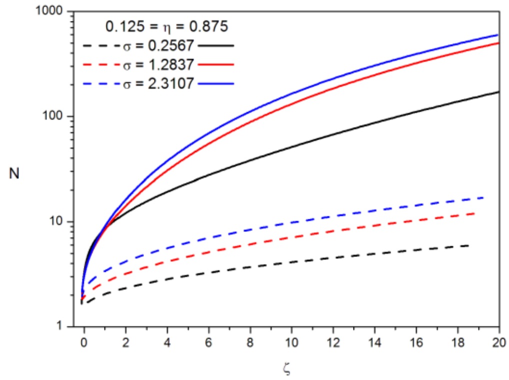

Fig. 6. Phase diagrams for thick (solid lines) and thin (dashed lines) antenna and various plasma radii

Axial profiles of plasma density are compactified in two groups. One of profiles created with thin antenna (η = 0.125, dashed lines) and another one – with thick antenna (η = 0.875, solid lines). Group with lower η is below the group with higher one. Plasma density increases with increasing of σ in both groups. At the beginning of column, plasma density of configuration with σ = 0.2567 and η = 0.875 (black solid line, the lowest in its group) is more ten times higher than N of configuration with σ = 2.3107 and η = 0.125 (blue dashed line, the highest in its group).

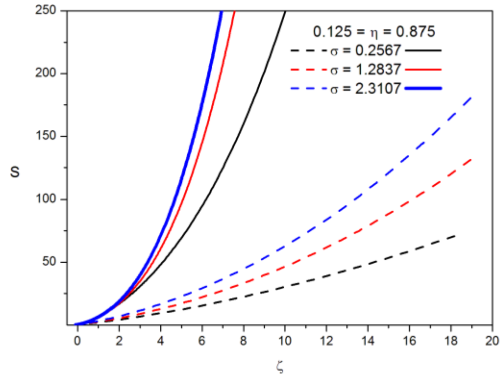

Fig. 7. Axial distribution of wave power flux for thick (solid lines) and thin (dashed lines) antenna and various plasma radii

Axial profiles of wave power flux are grouping in similar groups by same criteria.

4. Conclusions

Summarizing the results, presented in paper one can see that plasma column density in metal – vacuum – plasma configuration strongly depends on geometry factor η and plasma parameter σ.

If η is constant, N is increasing when plasma radius R (plasma parameter σ) increases.

If σ is constant, plasma density is increasing when vacuum layer decrease (η increase).

The highest plasma density is obtained when both η and σ are high and then the necessary wave power for sustaining the discharge is also the highest. With increasing the wave power the length of the plasma increases and new part of the plasma with higher density is added while the part closer to the end keeps the same plasma and wave characteristics.

5. References

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