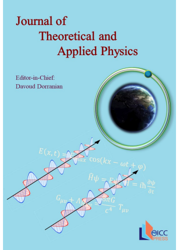

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Temperature effects role on the plasma antenna radiation pattern

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Abstract:
The radiation and propagation characteristics of a plasma column is theoretically studied in isothermal/non-isothermal regimes. The Boltzmann and Maxwell equations are employed to derive the radial profile of the electron temperature, electron density and the field components. It is found that by increasing the plasma density the plasma system goes toward the non-isothermal regime. It is shown that for the high values of the electron density, the isothermal approach would be violated and it must be replaced with the non-isothermal approach. This model is applicable to the plasma column with azimuthally symmetric plasma density. The present results are important from practical point of view and can be used in design and tuning of the plasma antennas.

Keywords: Plasma antenna; Non-isothermal approach; Plasma waveguide

1. Introduction

Investigation of basic features of surface waves propagating on the plasma column by Trivelpiece and Gould [1], has been attracted a great deal of attentions and opened a new field in plasma physics [2, 3]. Moisan tested experimentally excitation of the surface waves on a cylindrical plasma structure [4]. Numerous reasons motivate us to study such investigations, that use the surface waves in such basic problems as nonlinear interactions such as parametric instabilities, absorption of laser power by dense plasmas, and plasma heating by electromagnetic fields. The propagation of surface electromagnetic waves along the plasma column including the different azimuthal configurations makes it possible to determine the radial profiles of the electron plasma density [5]. Also, some applications of surface electromagnetic waves in the field of plasma microwave devices can be find in Refs [6–13].

Over the years, some studies have been conducted on the possibility of producing a plasma column and its sustaining by the surface wave propagating along the plasma column [14–18]. Surfatron is a physical device that has been designed to create a plasma column by launching an azimuthally symmetric surface wave [19, 20]. The work pressure of surfatron ranging approximately from 1 mTorr to atmospheric pressures which can produce plasma with number densities from 10^{10} to 10^{13} cm^{-3}, due to the power and geometric properties of surfatron. For example, in order to excite a plasma column with 80 W of power at frequency of 0.5 GHz, it needs to a chamber of 2.5 cm diameter and 1.8 m long. Other important features of the plasma surfatron which makes it interesting for a useful alternative for usual positive columns include the low density fluctuations and its productivity. The main applications of plasma surfatron reads as laser excitation, plasma chemistry, plasma antennas and also plasma medicine [21].

One of the most fascinating aspects of a plasma column is that the plasma column has been known as a folded monopole antenna working at radio frequency range [22]. Borg and Harris [23] proposed a plasma column working as a reconfigurable radiofrequency antenna. Then, a number of simulation and experimental efforts have been designed to improve the plasma antenna system.

A pioneering theoretical and experimental study has been done by Rayner et al. [24] on the basic features of plasma antennas working at VHF and HF radio frequencies produced by the surface waves. Also a theoretical model has been proposed by Ye et al. [25] to investigation of the surface wave propagation in the plasma antenna structures that predicts the radiation pattern for the plasma antennas. Kumar [26] and Anderson [27] proposed an interesting reconfigurable model for the plasma antennas. Moreover, a number of authors have investigated the resonant situation of the plasma antennas. A comparative study of metal and plasma antennas has been presented in references of [28,29]. Experimental, numerical and theoretical investigation of monopole plasma antennas [30–34]; radiation properties and circuit modeling of dipole plasma antennas [35–40] has been discussed by many researchers.

Plasma antenna analysis requires determination of the basic features of the plasma column employed in the plasma antenna, including collision frequency, plasma frequency, and longitudinal and transverse plasma permittivity. So far, two methods have been proposed for the production of plasma, with the help of electrodes and without electrodes [41, 42]. In the first one, the DC and capacitive coupling (either inner or outer electrodes) excitation are more common than other methods. The properties of DC and capacitive coupling- generated plasma are discussed in Refs [43] and [44,45], respectively. In the second method the plasma column is produced via the excitation of the surface waves by a launcher [46–48]. By changing the pressure inside the chamber as well as the excitation power, the length of the plasma and consequently the length of the plasma antenna can be controlled. Excitation is performed in several methods, including microwave and helical excitation, and inductive coupling [49, 50]. The produced plasma column in the electrodeless method, is inhomogeneous both in the axial and radial directions [46]. Then, the fine description of antenna regime of plasma column by Borg et al. [51] along with the theoretical and experimental investigations on the radiating behavior of plasma column has been a topic of interesting research over the last decades.

To pinpoint how the plasma column works as plasma antenna it may be noted that the plasma forms via ionization of neutral gas and a plasma appears as a conductor medium (for the frequencies below the plasma frequency ω_p) radiating at radiofrequency range. Then, the communication features occur and hence the plasma can be used as a radiofrequency antenna with small radar cross section. By de-energized the plasma, the mentioned plasma antenna losses conductivity and become a dielectric medium with negligible radar cross section. The latter fast "on-off" ability lets the plasma antenna to be an appropriate apparatus for military systems. It must be mentioned that the phase velocity in usual metal antenna is equal with the light velocity, thus the wave frequency becomes only a linear function of the wavenumber quantity. This turns out that the wave frequency is only parameter effecting on the radiation patter of metal antenna. This situation is completely different in the plasma antenna, as the radiation pattern in addition to the wave frequency would be function of electron number density and collision frequency. Such property provides the plasma antenna to be a configurable structure. This type of antenna is, indeed, of rapidly growing interest in many subjects of communication field such as plasma switched antennas (for radio-telescope arrays and mobile phones) [26], narrow-beam antennas [51], stealth aircraft [52], etc. Such wide range of application is due to some advantages of plasma in comparison with the metal one (for example fast switching on-off , small radar cross-section, etc).

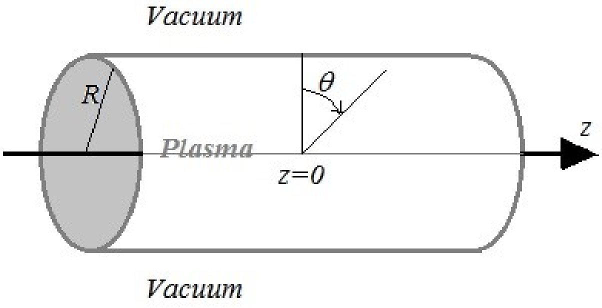

Figure 1. A schematic view of plasma antenna.

In this study, our aim is investigation of the radial profile of the electron temperature and electron density; and its influence on the propagation and radiation characteristics in the plasma column with azimuthal symmetric structure, such as surfatron discharge system. The present finding shows that the radial distribution affects significantly the propagation features of plasma column and can be used in design of the tunable plasma antenna structures.

Also, it is shown that by increasing the plasma density, the classical ambipolar diffusion model is not valid and plasma goes to obey the non-isothermal regime. Thus, we employed the Boltzmann equation and Maxwell equations to describe the radial transport and continuity of plasma species which allows us a self-consistent derivation of the radial profile. The results of two isothermal and non-isothermal approaches is compared in the high plasma density regime.

2. Fundamental equations

Let us consider a plasma column confined by a Pyrex tube of radius R sustained by a surface wave. A schematic view of plasma column is shown in Fig. 1. The electron density changes along the radial direction to reach a minimum value at $r \sim R$. By decreasing the electron density, the essential condition for the plasma discharge may be lacks. This turns out that there is a critical value for the electron density, i.e., $n_{cr} = m\varepsilon_0\omega^2/e^2$ [53] with ω being the wave frequency, which the essential condition for the propagation of the surface waves on the plasma column is $n > n_{cr}(1+\varepsilon_g)$, with ε_g being the vessel permittivity.

Here we try to consider a radial inhomogeneous in plasma density according to the surfatron plasma situation, to investigate its influence on the radiation pattern of plasma column. It is similar to a classical situation else that the electric field increases with radius. Accordingly, the electron temperature as well as the ionization frequency rises along the radial direction. In order to describe the radial transport and continuity of electron and ion species, we employ the moments of the Boltzmann equation in cylindrical geometry as

$$\frac{1}{r}\frac{d}{dr}(rnu) - \nu_I n = 0 \tag{1}$$

$$u\frac{d}{dr}u = \frac{e}{m}\frac{d}{dr}\phi - \frac{k_B}{mn}\frac{d}{dr}(nT_e) - \nu_e u \tag{2}$$

$$u\frac{d}{dr}u = -\frac{e}{M}\frac{d}{dr}\phi - \frac{k_B T_i}{Mn}\frac{d}{dr}n - \nu_i u \tag{3}$$

where $\nu_{e,i} = \nu_I + \nu_{(e,i)n}$, ν_I, u, $\nu_{(e,i)n}$, and ϕ, are respectively the ionization frequency (which is an increasing function of r), the radial drift velocity (of e and i species), the electron (ion)-neutral collision frequency, and the electrostatic potential. To write the basic equations (1)-(3) we used from two assumptions: the first one is that the plasma to be quasi-neutral (i.e., $|n_i - n_e|/|n_i + n_e| \ll 1$) and the latter one is that the distribution function of electron species is Maxwellian in its isotropic part. In the following, we ignore the electron inertial which yields us an expression for the radial drift velocity of the electron species as follows:

$$u = \mu_e \frac{d}{dr}\phi - \frac{D_e}{n}\frac{d}{dr}n - \frac{\tau_e}{n}\frac{d}{dr}T_e \tag{4}$$

where μ_e represents the electron mobility, τ_e is the thermal diffusion coefficient given by $n\partial D_e/\partial T_e$, D_e is the electron free diffusion coefficient given by $\mu_e k_B T_e/e$. Let us restrict our attention to the case of azimuthal symmetry in the following, hence, the TM mode (E_r, H_φ, E_z) describes the guided wave solutions with the complex wave vector $k = \beta + i\alpha$ directed along the plasma column axis (with β and α being respectively the propagation and attenuation coefficients).

In order to find the possible guided wave solution, we solve the Maxwell equations simultaneously, that leads to the following differential equation fir the electromagnetic field as

$$\left(\nabla^2 + \varepsilon \frac{\omega^2}{c^2}\right)\begin{Bmatrix} E \\ H \end{Bmatrix} = 0 \tag{5}$$

Due to the azimuthal symmetry in cylindrical geometry we assume that

$$\begin{Bmatrix} E \\ H \end{Bmatrix} = \begin{Bmatrix} E(r) \\ H(r) \end{Bmatrix} e^{ikz - i\omega t} \tag{6}$$

It can prove that the axial component of the electric field satisfies the following differential equation

$$\frac{d^2E_z}{dr^2} + \left(\frac{1}{r} - \frac{1}{\varepsilon_p}\frac{\beta^2c^2}{\omega^2\varepsilon_p - c^2\beta^2}\frac{d\varepsilon_p}{dr}\right)\frac{dE_z}{dr} + (\frac{\omega^2}{c^2}\varepsilon_p - \beta^2)E_z = 0 \tag{7}$$

where ε_p is the plasma permittivity given by $1 - \omega_p^2/\omega(\omega + i\nu)$. It is convenient to introduce the dimensionless quantities in the numerical analysis, as $\Phi = e\phi/Mv_s^2$, $U = u/v_s$, $\xi = \nu_{1n} r/v_s$ and $N = n/\bar{n}$ where $v_s = \sqrt{k_B T_{e0}/M}$ is the ion acoustic speed, $\bar{n} = 1/R^2 \int_0^R n(r) r dr$ is the mean plasma density and T_{e0} is the electron temperature at the z-axis. Accordingly, Eqs. (1), (3), (4), and (7) take the following normalized form as

$$\frac{1}{\xi}\frac{d}{d\xi}(N\xi U) = \frac{\nu_I}{\nu_{in}} n \tag{8}$$

$$U = \bar{\mu}\frac{d\Phi}{d\xi} - \bar{D}\frac{1}{N}\frac{dN}{d\xi} - \bar{\tau}\frac{1}{N}\frac{dT_E}{d\xi} \tag{9}$$

$$U\frac{dU}{d\xi} = -\frac{d\Phi}{d\xi} - \frac{T_I}{N}\frac{dN}{d\xi} - \bar{\nu}U \tag{10}$$

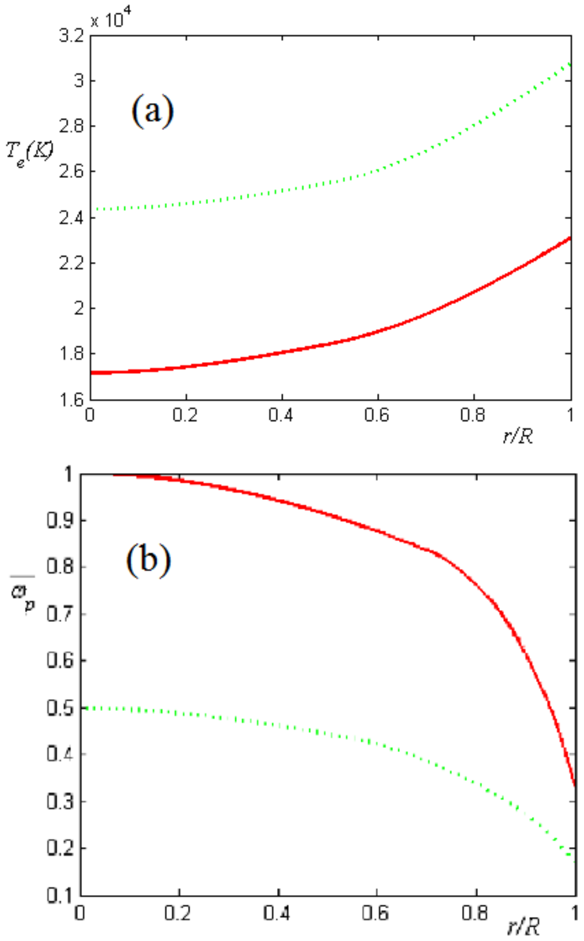

Figure 2. (a) Radial profile of electron temperature for $\bar{n} \sim 4 \times 10^{11}$ cm^{-3} (solid line) $\bar{n} \sim 1 \times 10^{11}$ cm^{-3} (dotted line) and (b) Radial profile of plasma frequency for $\bar{n} \sim 4 \times 10^{11}$ cm^{-3} (solid line) $\bar{n} \sim 4 \times 10^{11}$ cm^{-3} (dotted line).

$$\frac{d^2\varepsilon}{d\xi^2} + \left(\frac{1}{\xi} + \frac{1}{N(w^2 - N)}\frac{\bar{\beta}^2}{w^2 - N - \bar{\beta}^2}\frac{dN}{d\xi}\right)\frac{d\varepsilon}{d\xi} + (w^2 - N - \bar{\beta}^2)\varepsilon = 0 \tag{11}$$

where $\bar{\mu} = \mu_e M \nu_{1n}/e$, $\bar{D} = D_e \nu_{1n}/v_s^2$, $\bar{\tau} = \tau_e T_{e0} \nu_{1n}/\bar{n} v_s^2$, $T_E = T_e/T_{e0}$, $T_I = T_i/T_{e0}$, $\omega_{p0} = \sqrt{\bar{n}e^2/m\varepsilon_0}$, $\bar{\beta} = c\beta/\omega_p$ and $\bar{\nu} = \nu_i/\nu_{1n}$. The equations system of (8)-(11) can be solved through a standard numerical method (for more detail see the appendix. A).

The wave number β which appears in different coefficients in our basic equations is an unknown quantity that must be determined. Generally, the dispersion relation can be obtained from the appropriate boundary conditions (i.e., continuity of tangential component of the fields at the plasma boundary). The effect of density inhomogeneity on the dispersion characteristics is negligible for $\beta R < 1$ [54], since such condition is valid in most physical situations, we can instead employ the dispersion relation of a homogeneous plasma [55].

3. Numerical analysis

In order to numerical analysis of the present physical situation, we use the experimental data [55] derived for typical working conditions in a surfatron discharge with argon gas. An argon discharge at pressure of 0.05-0.5 Torr, with radius of 2.5 cm, and dielectric permittivity of ε_g= 4.52 working at frequency 600 MHz, was used in the surfatron discharge. The radial variation of the electron temperature and plasma frequency is shown in Fig. 2, for two different parameter sets. It can be seen that the electron temperature increases with increase of radial distance, while the electron density shows an inverse behavior. We found that an increase in the electron density decreases the electron temperature. This situation can be explained by the fact that for the small values of electron density, the plasma system is isothermal and becomes non-isothermal as the electron density increases. At the high values of the electron density, the ionization rate experiences an enhancement toward the plasma boundary, that turns out the plasma discharge compensates the losses phenomena with the lower values of electron temperature. Therefore, by increase of the electron density, the isothermal approach would be violated and the non-isothermal view must be considered, which this is more pronounce for the higher values of the electron density. The difference between such profile with the isothermal case can be described by the increasing behavior of the ionization rate near to the plasma boundary. Since the practical plasma is not completely homogeneous, one has to consider the spatial dependence of the plasma parameters. It is seen that in rare plasma, the density dependence of the ionization rate and the field intensity is also weak. Meanwhile, by increase in the plasma density, variation of the ionization rate shows a sharp increase toward the plasma boundary.

The radial variation of the normalized wave number is represented in Fig. 3, for two different values of the equilibrium electron density. It can be seen that the radial wave number has a slow increasing behavior with radial coordinate and this becomes sharper near to the periphery. The higher values of the electron density are corresponding with the lower values of the wavenumber. This is because of the direct dependency of plasmon frequency on the plasma density.

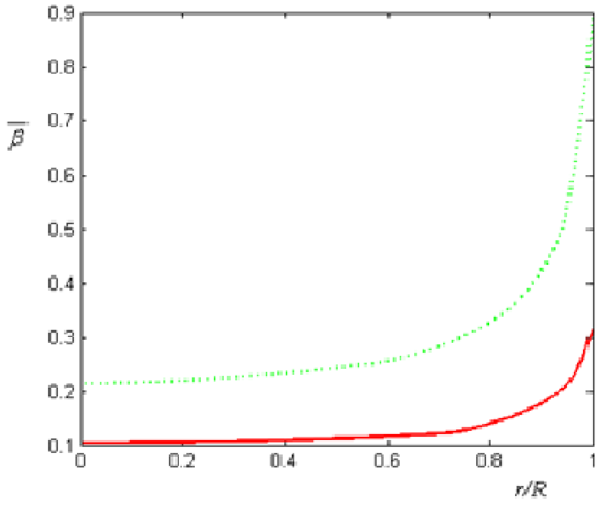

Figure 3. Radial profile of propagation coefficient, for $\bar{n} \sim 4\times10^{11}$ cm^{-3} (solid line) $\bar{n} \sim 1\times10^{11}$ cm^{-3} (dotted line).

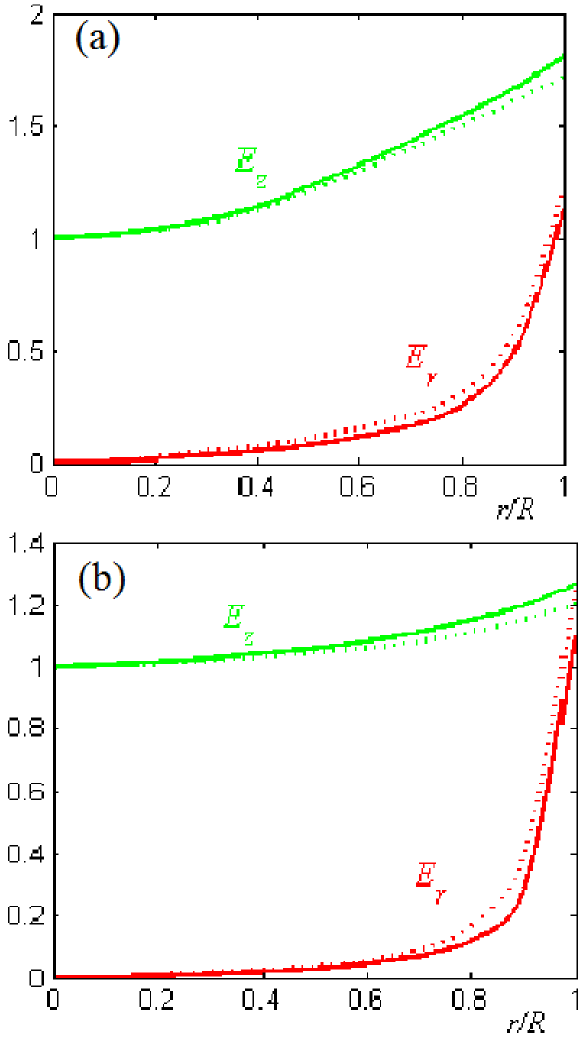

Figure 4. (a) Radial and axial profile of electric field for $\bar{n} \sim 4\times10^{11}$ cm^{-3} from two isothermal (dotted line) an non-isothermal (solid lines) approaches and (b) Radial and axial profile of electric field for $\bar{n} \sim 1\times10^{11}$ cm^{-3}, from two isothermal (dotted line) an non-isothermal (solid lines) approaches.

The normalized axial and radial components of the electric field excited at ω/ω_{p0} ~0.11 (panel-a) and ω/ω_{p0} ~0.22 (panel-b) exhibited in Fig. 4. It can be seen that the radial electric field is very smaller than the axial component near to the axis, while a sharp increase occurred in the radial component near to the wall. This is due to the radial profile of electron density, that decreases toward the periphery. A comparison between panels-(a) and (b) shows that the radial component of the electric field in the dense plasma is weaker than that of the dilute plasma, while the axial component of electric field shows an inverse behavior. Also we found that the isothermal approach cannot give a complete description for the dynamical behavior of plasma system when the plasma density is enough high to obey the non-isothermal regime. In the non-isothermal regime, the isothermal approach estimates the axial (radial)

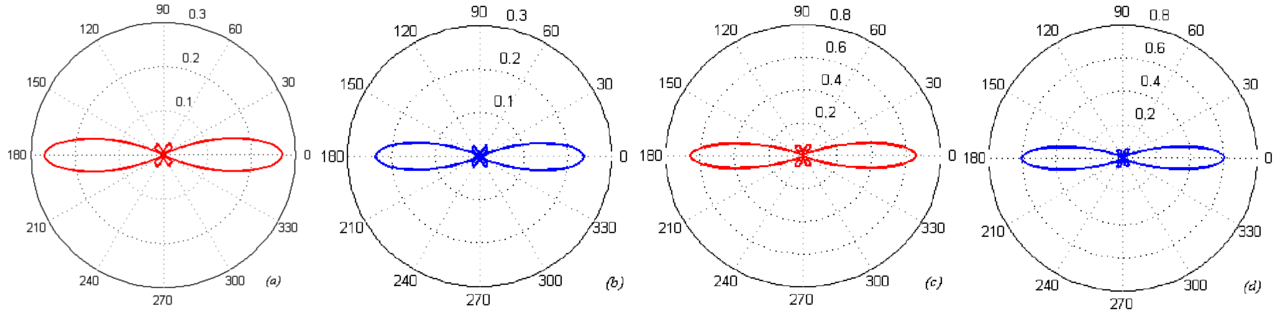

Figure 5. (a) Radiation pattern of plasma column for a=2.5 cm, $\bar{n} \sim 4 \times 10^{11}$ cm^{-3} (isothermal approach), (b) Radiation pattern of plasma column for a=2.5 cm, $\bar{n} \sim 4 \times 10^{11}$ cm^{-3} (non-isothermal approach), (c) Radiation pattern of plasma column for a=2.5 cm, $\bar{n} \sim 1 \times 10^{11}$ cm^{-3} (isothermal approach), and (d) Radiation pattern of plasma column for a=2.5 cm, $\bar{n} \sim 1 \times 10^{11}$ cm^{-3} (non-isothermal approach).

electric field smaller (larger) than that of the non-isothermal approach.

Figures 5 (a)-(d) indicates a comparison between the radiation pattern obtained by two isothermal and non-isothermal approaches for two different non-isothermal regimes. It can be seen that the isothermal approach predicts a similar radiation pattern with higher strength relative to the non-isothermal approach. It can also be seen that the radiation strength decreases with increase of non-isothermality. It is known that the electron density has an inverse dependence on the electron temperature. Indeed, at the low values of the plasma density, the field magnitude and the ionization rate increase softly with radius and cause the plasma stay at isothermal regime. On the other hand, for the higher values of the plasma density, variation of the ionization rate occurs sharply and the essential temperature value for maintain the plasma discharge against the loss phenomena are smaller.

4. Conclusion

It is found that for so many physical situations, such as in the wave propagation plasma, the resonance and radiation of plasma column, it is essential to consider the plasma density profile. Also accordingly in many practical situations, such as surfatron, simple discharge models are strictly appropriate, because of different radial distributions of electron density from those of simple models. The specific characteristic of such profiles are concerned to the evanescent features of surface waves inside the plasma medium. Indeed, the amplification of the wave field toward the periphery, the electron temperature increases and thus the gas excitation occurs more efficiently near the plasma column boundary. In this case, a detailed analysis not trivial because of the complexity of electron density profile and that the collision frequency would be function of the electron density and temperature of colliding species.

In this case, the electron density profile is enough complex to be described by simple models and also the ionization rate would be function of the electron density and temperature of the colliding species. The classical ambipolar diffusion model is not valid here, and we employed the Boltzmann equation and Maxwell equations to describe the radial transport and continuity of plasma species which let us to self-consistent derive the radial profile of n, T_e, E and H, for typical physical parameters. It is shown that the nonisothermality and radial profile of the electron density and temperature must be considered as an important phenomenon in designing of a plasma column as a plasma antenna. It is found that the temperature and density profiles of the electron species are sensitive to function of radial coordinate in a real situation such as in the surfatron discharge.

Since the plasma system with high electron density goes to obey the non-isothermal regime, the usual isothermal approach cannot provide a complete description for the high density regime. A comparative study is done to show that the isothermal approach is not valid for the high density plasma regime. It is found that the isothermal approach predicts the axial electric field smaller than that of the non-isothermal approach while the estimated radial electric field is higher than the expected value. About the radiation pattern, however the pattern predicted by isothermal approach is similar to that obtained by non-isothermal approach, but the isothermal approach predicts a higher amplitude for the radiation.

Since the radiation pattern of a plasma antenna can change at a fixed excited frequency, via changing of the plasma density or electron temperature, the desired radiation pattern can be created by appropriated choice of the plasma parameters. This shows that why the plasma antenna attracted a great deal of attention. The present results are important from practical point of view and can be used in design and tuning of the plasma antennas.

Appendix. A:

In order to solve Eqs. (8)-(11), we used the numerical procedure by Matlab software. The normalized velocity is considered as an independent variable where the normalized velocity takes the values of $U = 0$ and $U = 1$ at axis and the plasma boundary, respectively. Then, the integration is carried out on the interval $0 \leq U \leq 1$, keeping fix the other quantities. The other initial conditions are $\xi|_{U=0} = 0$ and $\varepsilon|_{U=0} = 1$. It is assumed that the plasma boundary occurred at $r = R$ or $\xi(1) = \nu_{in}R/v_s$. The convergence rate is dependent on the initial values of N and T_E. Then, the numerical solution of the electromagnetic fields, the plasma density and electron temperature can be obtained as a function of radial coordinate.

Conflict of interest statement
The authors declare that they have no conflict of interest.

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