Three-Dimensional Model of Cylindrical Monopole Plasma Antenna Driven by Surface Wave

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Abstract: In the recent research on cylindrical monopole plasma antenna excited by surface wave, several basal theoretical problems for the radiation of plasma antenna are investigated. Many meaningful results about plasmas antenna, e.g. the analysis of physical characteristics, numerical calculation methods, software simulation, diagnosis of parameters, etc. have already been obtained. As known that the plasma antennas have reconfigurable properties and many physical parameters of plasma antenna are governed by the applied electromagnetic field and actual coupling method, so model research of plasma antenna is very necessarily in its further investigations and applications. But the precise model of monopole plasma antenna according to its three-dimensional structure has not been proposed yet, the three-dimensional model is proposed in the paper, three-dimensional distributions of electric and magnetic fields around monopole plasma antenna are analyzed. The related formulas and equations of the model are derived by applying molecular dynamic theories and Maxwell-Boltzmann equations; in addition, numerical simulation methods are adopted to verify validity of the proposed model.

*Key-Words: C*ylindrical Monopole Plasma Antenna; Surface wave; Three-Dimensional Model; Calculation

1 Introduction

Despite the progress in recent study on cylindrical monopole plasma antenna driven by surface wave, the precise calculation model of it has not been established yet. Experiments performed before have verified that plasma antenna has many properties similar to metallic antenna, but there do exists obvious differences between plasma antenna and metallic one, the state of plasma is unstable; whose density presents linear variation or nonlinear distributions and the parameters of plasma antenna are variable, which cause plasma antennas have reconfigurable properties in parameters, so the modeling analysis of plasma antenna are very necessary on its further research. Some basic experiments on plasma antenna have already been completed to aid in the understanding of plasma antenna; the researchers from the plasma antenna laboratory in Australian National University have completed some physical research and achieved some characteristics of plasma antenna [1, 2, 3].

A.D.Cheetham studied the parameters of plasma antenna and the control system of the plasma antenna excited by RF spiral wave energy. G.G.Borg completed the characteristics research, e.g. the radiation efficiency, signal amplitude and noise amplitude of monopole plasma antenna. G.G.Borg and J.H.Harris' research work indicated that there is a wide varying range for the electrical parameters of plasma antenna, enjoying a good application prospect in RF communication field [1]. They have verified that when the excited power is variable, current distribution of plasma antenna also will be changed according to the changing power. J.P.Rayner and M.Hargreave presented the experimental results of the plasma density distribution of noise of antenna, and radiation pattern in their review articles [4,5,6,7]. The experimental investigations have shown that although there exists certain loss of radiation efficiency due to the lower conductivity of the plasma column, the loss can be easily made up through boosting the propagation wave power, and the cone shaping distribution of density and conductivity of plasma antenna have little effect on its radiation capability.

The preliminary and basic model research results have been given out in the academic journals [8-11], but the modeling method in the article mentioned above can reflect the characteristics of the plasma antenna precisely, so the further model research is very essential , if we want to get a thorough understanding of the plasma antenna.

The study of the regularity and abnormal characteristics of plasma antenna is carried out through modeling method in the paper. As it is known that only the analysis of relationships between particle motion and physical properties of plasma antenna are made, then complete understanding of the monopole plasma antenna can be obtained. The modeling research of the plasma antenna is to form a method able to predicate the state of plasma antenna; the relationships between the electron motion and reconfigurable parameters of plasma antenna can be obtained through model analysis. The analysis of three-dimensional model proposed in the paper is based on the molecular dynamics theory and Maxwell-Boltzmann equations. The average statistical results of particle motion are gained by applying statistical physics and mathematical tools.

This paper is organized as follows. In Section II, the structure descriptions of the plasma antenna are given out. The three-dimensional Equations for electromagnetic fields and the boundary conditions of the plasma antenna are established and related theoretical descriptions are presented. In Section III, theory analysis based on the Boltzmann-Maxwell Equations are made and numerical solutions are provided. From the solutions, it is found at the parameters of plasma antenna can be obtained from the Boltzmann-Maxwell Equations. In Section IV, the relationships between the electron energy distribution function (EEDF) and the other parameters of plasma antenna are analyzed in detail. Analysis demonstrates that the plasma antenna has reconfigurable properties. The three-dimensional model is also verified by the related experiments. The conclusions are established in Section V.

2 Analysis of Electromagnetic Field

In order to make the precise analysis of plasma distribution, the cylindrical coordinates is adopted in the analysis. In the model, the forces of macroscopic collision and microscopic collision are considered, respectively, and then the calculations of density distribution of plasma, dielectric coefficient, and electric conductivity, etc. can be carried out. The structure of cylindrical monopole plasma antenna analyzed in this paper is shown in the Fig.1, the plasma antenna is made up of glass tube, in which is filled with argon gas with certain pressure. In he plasma antenna system there exists two signal circuits, one is excited RF power, the other is the propagation signal transmitting along the antenna, which can be seen in the Fig.1

The cylindrical RF coupling structure is illustrated in Fig.2. In order to simplify the discussion process, the assumptions are made as follows, R represents the radius of antenna, L represents the length of plasma antenna, N represents the number of the RF coil, I denotes the RF current and ω denote frequency of excited power.

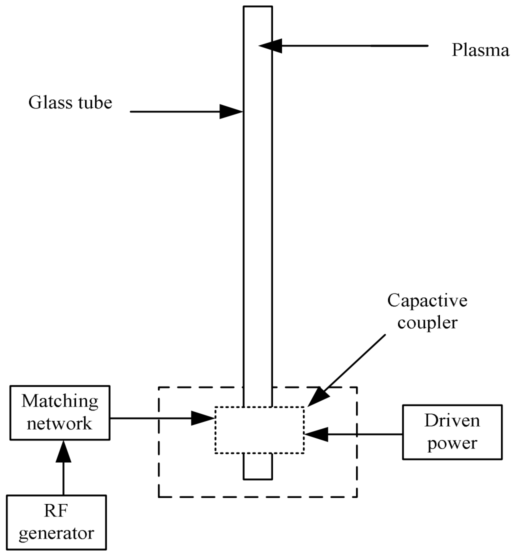
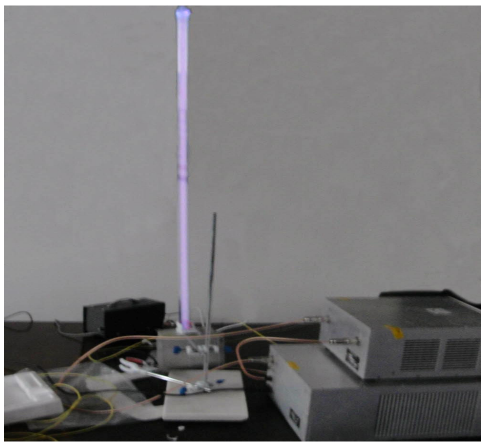


Fig.1 Structure of cylindrical monopole plasma antenna driven by surface wave



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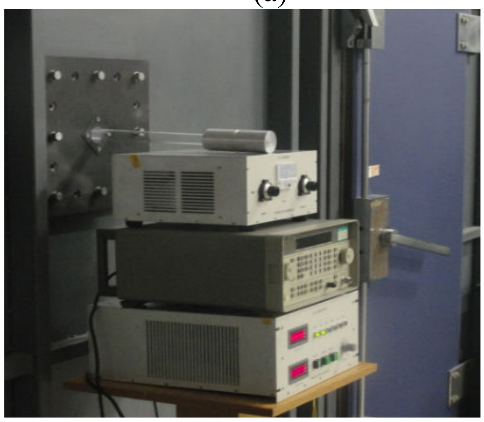

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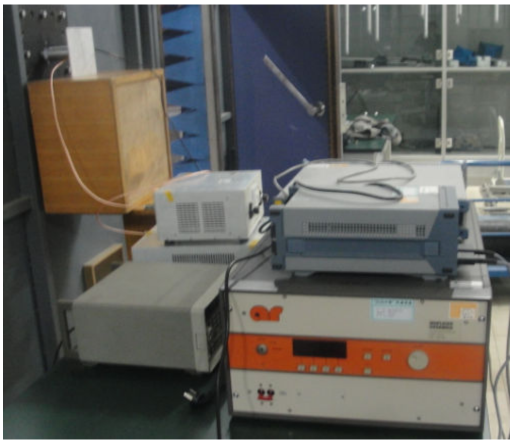

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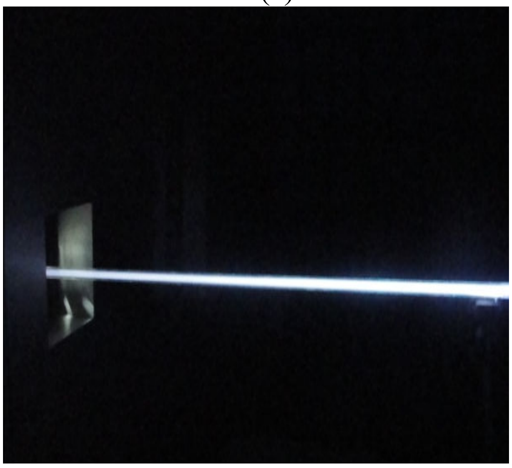


(d)

Fig.2 Photos of cylindrical monopole plasma antenna driven by surface wave

As shown in the Fig.2, the related experiments of the test are performed in the microwave anechoic chamber, the highest excited power of plasma antenna is about 200W, and the frequency of the driven signal is about 80MHz, and the signal generator of the Agilent is adopted.

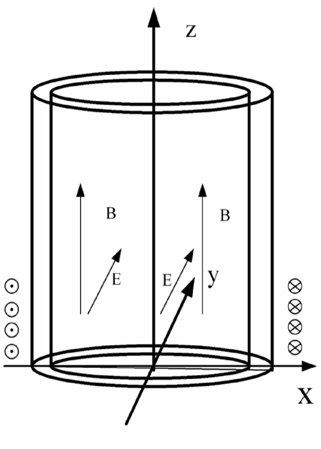


Fig.3 Electromagnetic field distribution around the plasma antenna

The cylindrical monopole plasma antenna excited by surface wave is illustrated in Fig.3. In the three-dimensional coordinates, the electric field and the inductive magnetic field present cylindrical symmetrical distributions.

The electric field can be expressed as (1).

$$E_{rf} = [E_r(r,z)e_r + E_z(r,z)e_z]e^{-i\omega t} \tag{1}$$

The inductive magnetic field is expressed as (2).

$$B_{rf}(r,t) = \left[B_r(r,z)e_r + B_z(r,z)e_z\right]e^{-j\omega t} \tag{2}$$

The boundary condition of the equations can be expressed as (3) and (4).

$$\begin{cases} E_r(r,0) = E_r(z) \\ E_r(\infty,0) = 0 \\ E_z(r,l) = E_r(z)\cdot\alpha \\ E_z(r,\infty) = 0 \end{cases} \tag{3}$$

$$\begin{cases} B_z(r,0) = B_r(z) \\ B_z(\infty,z) = 0 \\ B_r(r,l) = B_r(z)\cdot\beta \\ B_r(r,\infty) = 0 \end{cases} \tag{4}$$

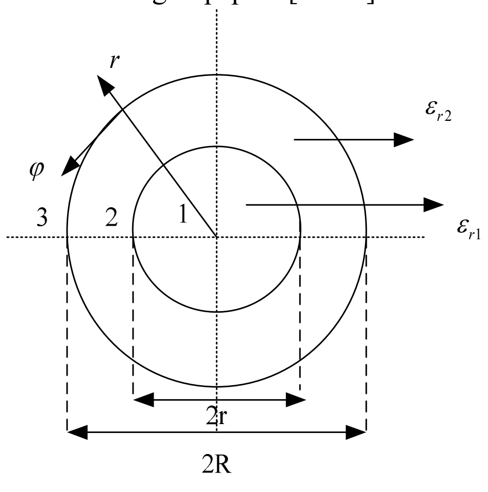
Where $E_r(z)$ represents magnetic field and $B_r(z)$ represents electric field, respectively in the boundary of the plasma antenna, which are determined by the RF electric field; a represents the variable distance, α and β are the attenuation factors of the magnetic and electric fields around the plasma antenna. The coils can be regarded as a series of current sources; the electric field $E_r(r,z)$ presents the distribution of Bessel functions.

When the plasma frequency and collision frequency are different, the surface current distribution also will be different, which will causes the different distribution of electric field. When the frequency of the plasma is low and the frequency of particle collision is high, the surface current distribution will present attenuation distribution; with increase of the plasma frequency and reduction of the plasma collision, the axial current presents cyclical alternation. The axial electrical distribution of the plasma antenna can be obtained through the current distribution functions.

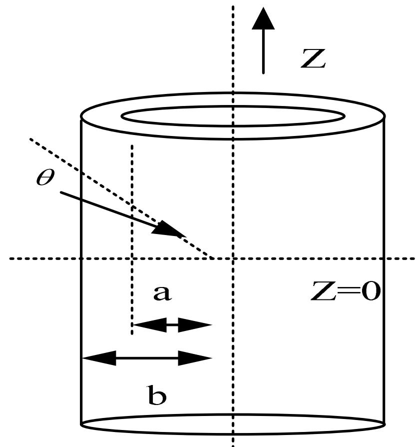
The physical parameters such as conductivity and permittivity, etc. are all determined by movements of electron and ion of the plasma. The numerical values of physical parameters such as the conductivity and the dielectric factor can be calculated out through the Boltzmann-Maxwell equation.

The physical model of the plasma antenna is as shown in Fig.4. For a convenient investigation of EM wave distribution, the boundary in the z-direction is neglected. Because the plasma density decreases very slowly along the axial direction, Region 1 could be considered to be filled with low-temperature high homogeneous density plasma, and we assume that the length of the plasma column that can carry EM wave propagation is less than the practical length of plasma antennae. Region 2 is a homogeneous medium, region 3 is free space. Define ε_{r1} and ε_r as the relative permittivity of plasma and medium, respectively. The diameter of the system is 2R, the diameter of the plasma column is 2r, and the thickness of medium cladding is R-r . The plasma relative permittivity is $\varepsilon_r = 1-(\omega_p/\omega)^2$ in which ω_p is plasma frequency and ω is the EM wave frequency. According to the rule of plasma antenna excitation [11], the EM wave cannot propagate in low-temperature high homogeneous density plasma when $\omega < \omega_p$. Under this condition, the EM wave will propagate along the interface between plasma channel and medium tube as a surface wave. Here we assume that a TM plane wave whose frequency is lower than the plasma frequency is fed into the plasma antenna.

As we known that the distributions of electromagnetic fields around the plasma antenna are very complex. And related equations of the EM fields in cylindrical coordinates satisfy The Helmholtz equation, and precise research works have presented by researchers. The equations of the EM fields in different region around the plasma can be obtained according to papers [11-13].



(a)



(b)

Fig.4 Simplified physical structure of the plasma antenna

As shown in the Fig.4, in the inner side of the plasma column, the plasma also can be divided in to many parts; the sheath of the plasma also should be taken into consideration if needed. The wave will transmit to inner region from the outer interface, and the signal also will propagate along both the radial and axial directions in different regions, and as known that the wave transmits along the radial direction of the plasma antenna, the amplitude of the EM energy will decay along the this direction.

When signal wave is fed into a plasma antenna, radiation modes and transmission modes co-exist in some frequency bands. In the experiments we find that the high radiation modes appear gradually as the frequency of signal rises. The transmission modes only exist in specific frequency bands. In the case of transmission modes, we can control these modes by changing the frequency of the signal and relevant parameters of the plasma. In our experiment, the plasma antenna is excited by two kinds of radiation mechanisms: one is the m-radiation which is caused by the oscillation of disturbing currents on the interface between plasma and medium. The other one is d-radiation caused by EM wave transmission. The d-radiation modes excite interface disturbing currents between plasma and medium, and meanwhile the excited disturbing currents influence the transmission modes. Furthermore, due to transmission, the signal wave of transmission modes decays along the length of plasma antenna and becomes an attenuated travelling wave, so the disturbing currents excited by transmission modes also will be decayed. If the frequency of the signal fed is located in the frequency bands where some transmission modes do not appear, the noise impact on plasma antenna radiation will be vanished or decreased.

3 Analysis Based on Boltzmann Equation

Transport phenomena in plasma can be promoted by the external and by internal forces. In the spatially homogeneous plasma under the influence of external force a drifting of the electrons can occur. This motion induced by the external forces is referred to as mobility. Since the electrons have mass and electric charge, their motion implies transport of mass and conduction of electricity when acted upon by an external electric field. On the other hand, in spatially inhomogeneous plasma collisions cause the electrons to drift from the high-pressure to low-pressure regions. The existence of pressure gradients is associated with the existence of either density gradients or temperature gradients, or both. This motion of the electrons, induced by the internal pressure gradients, is called diffusion.

In the plasma antenna excited by the surface wave, we shall analyze the basic transport phenomena of electric conduction, particle diffusion, and thermal energy flux in the weekly ionized plasma, using the Boltzmann equation with relation model for the collision term and considering a velocity-dependent collision frequency.

When the plasma is in low temperature state, the velocity distribution function of electron is satisfied with the Boltzmann Equation. We can make the hypothesis that electrons in plasma antenna satisfy the Boltzmann Equation as below.

$$\frac{\partial f}{\partial t} + v\frac{\partial f}{\partial x} + \frac{\vec{F}}{m}\frac{\partial f}{\partial v} = S(f,q) \tag{5}$$

where $f = f(\vec{x},\vec{v},t)$ represents the electron velocity function, $\vec{x} = (x,y,z)$ represents the electron position vector; $\vec{v} = (v_x,v_y,v_z)$ represents the electron velocity vector; t represents time parameters; $\vec{F}$ represents sum of the force; m represents the quality of the electron; $S(*)$ represents the distribution function caused by collisions; q represents velocity distribution function of electron in the equilibrium state; f represents the velocity distribution function of electron in the non-equilibrium state.

The part of collision integral is very complex, and the numerical calculation is very difficult to perform. If the distribution functions are expanded into power progression by applying the variation principle, collision integral can be calculated to the approximate extent needed. If only the former two terms of the progression is kept in the calculation process, the complex calculation will be avoided; the linearization equation can be expressed as (6).

$$f = f_0 + f_1 \tag{6}$$

The Boltzmann Equation also can be written as (7).

$$\frac{\partial f}{\partial t} + v_x\frac{\partial f}{\partial x} - \frac{eE_f}{m_e}\cdot\frac{\partial f}{\partial v} = S(f) \tag{7}$$

$$f(r,v,t) = f_0(\varepsilon) + f_1(r,v)e^{-i\omega t} \tag{8}$$

$f_0(\varepsilon)$ represents the electron energy distribution function (EEDF); $f_1(r,v)$ represents the disturber distribution caused by the outer energy field, and the Equation (8) is satisfied with the condition $|f_1| << |f_0|$. If Equation (6) is put into Equation (5), the interference distribution can be obtained. $f_1(r,v)$ is also satisfied with the (9).

$$(v - i\omega)f_1^{\pm} \pm v_r\frac{\partial f_1^{\pm}}{\partial x} = ev_\varphi E_\varphi\frac{df_0}{d\varepsilon} \tag{9}$$

Where the sign $\pm$ denotes $v_r > 0$, $v_r < 0$, r and φ respectively represent the direction of r and φ in the cylindrical coordinates system; v_r and v_φ represent the velocity in direction of r and φ ; $\varepsilon = mv^2/2$ represents the kinetic energy of electron. In order to simplify the calculation, we adopt the new variable function (10) in the calculation process.

$$\begin{cases} F^+ = \frac{1}{2}(f_1^+ + f_1^-) \\ F^- = \frac{1}{2}(f_1^+ - f_1^-) \end{cases} \tag{10}$$

Then (11) and (12) can be obtained as below,

$$\begin{cases} (v - iw)F^+ + (v_x\frac{\partial}{\partial x} + \omega_c\frac{\partial}{\partial \phi})F^- = \frac{eE_y}{m_e}\frac{\partial f_0}{\partial v_y} \\ (v - i\omega)F^- + (v_x\frac{\partial}{\partial x} + \omega_c\frac{\partial}{\partial \phi})F^+ = 0 \end{cases} \tag{11}$$

$$f_1(r,z.v,t) = \sum_{n=-\infty}^{\infty}\sum_{k=-\infty}^{\infty}\left[\frac{ev_\varphi E_{nk}\sin(k_n r)\sin(k_k z)}{v - i\omega + ik_n v_r}\right]\frac{df_0}{d\varepsilon}e^{-i\omega t} \tag{12}$$

Where

$$k_n = n\pi/2r\ ,\quad E_{nk} = \int_{-r}^{r}\int_{0}^{l}[E_\varphi(r,z)\sin(k_n z)]drdz$$

If the disturb function is obtained, the density current can be worked out.

$$j_\varphi(r,z,t) = -\frac{1}{2\pi}(\frac{m_e}{2})^{\frac{3}{2}} en_0 \int dv f_1(r,z,v,t) = \sum_{n=-\infty}^{\infty}\sum_{k=-\infty}^{\infty}\left[\sigma_{nk}E_{nk}\sin(k_n r)\sin(k_k z)\right]e^{-i\omega t} \quad (13)$$

The surface current and electric field distribution can be worked out through proposed model. The conductivity of plasma in Fourier space can be obtained; dielectric constant and magnetic conductivity of plasma also can be worked out. The EEDF also can be got through the model equations deduced above. With the model proposed, the surface current distribution of the plasma antenna can be obtained, thus the parameters such as the radiation pattern; gain, etc. also can be got [14].

$$v_c = 1.52\times 10^7 P\sqrt{T_e} \quad (14)$$

The relationship between the collision frequency and the gas pressure is expressed as (15), where the v_c represents the collision frequency; P represents the inner pressure of the plasma antenna and the T_e represents the electron temperature of the plasma antenna.

With increase of the pressure, the collision frequency of plasma will be enhanced accordingly as shown in (15), and (15) can be obtained through complex deducing, f_p represents frequency of plasma; ω_p represents angle frequency of plasma; N represents density of plasma which is governed by the pressure and driven power [15].

$$f_p = \frac{\omega_p}{2\pi} \approx 8.98\sqrt{N[m^{-3}]} \quad (15)$$

Under the nonmagnetic condition, the relationship between the excitation frequency and the plasma antenna can be calculated from expression of conductivity (16), where σ represents conductivity of plasma.

$$\sigma = \frac{\varepsilon_0\omega_p^2}{(j\omega + v_c)} \quad (16)$$

It is known that the conductivity of plasma changes according to the frequency of excitation field. The dielectric constant will also change with the variation conductivity.

The permittivity will also be changed with changing of conductivity shown as (17), where σ_{ij} and ε_{ij} represent conductivity and permittivity of the plasma antenna under certain condition, separately.

$$\|\sigma_{ij}\| = j\omega\varepsilon_0(\|\varepsilon_{ij}\| - \|I\|) \quad (17)$$

As is known to us that the radiation pattern of antenna is determined by distribution of its surface current, the physical parameters, such as the conductivity, dielectric constant, surface current of the plasma antenna are all dominated by the EEDF of the plasma antenna, and related analysis already have presented in our papers [16,17].

4 Numerical Simulation and Discussion

The EEDF reflects the state of plasma and governs the parameters of plasma antenna. In this section, the relationships between the EEDF and the excited parameters of the plasma antenna are discussed. The numerical simulation method of this model is adopted to predicate and analyze the state of plasma antenna.

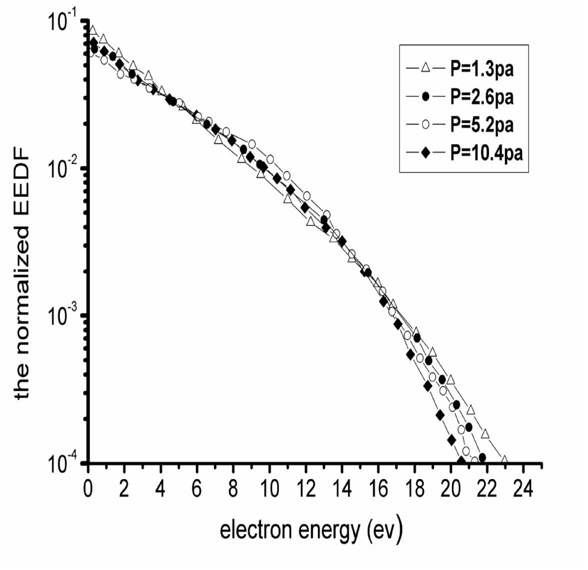


Fig.5 Influence of gas pressure on EEDF, other parameters: R=1cm, L=10cm, I=10A, n=1 f=13.56MHz

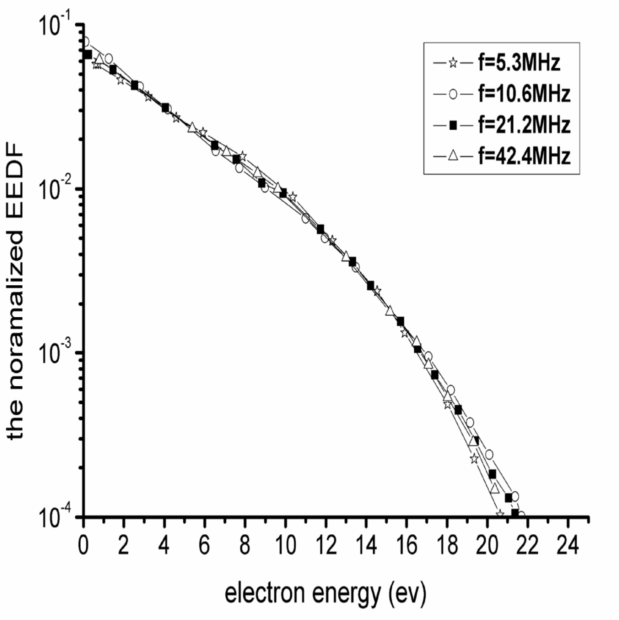


Fig.6 Influence of driving Frequency on EEDF, other parameters: R=1cm, L=10cm, I=10A, n=1, P=15pa

If the discharge gas is composed of hydrogen, plasma density is about $1.5\times10^{10}/cm^3$. R represents antenna radius; L represents antenna length, n is the number of RF coil and the internal pressure of plasma antenna is variable, external driven RF power is controllable.

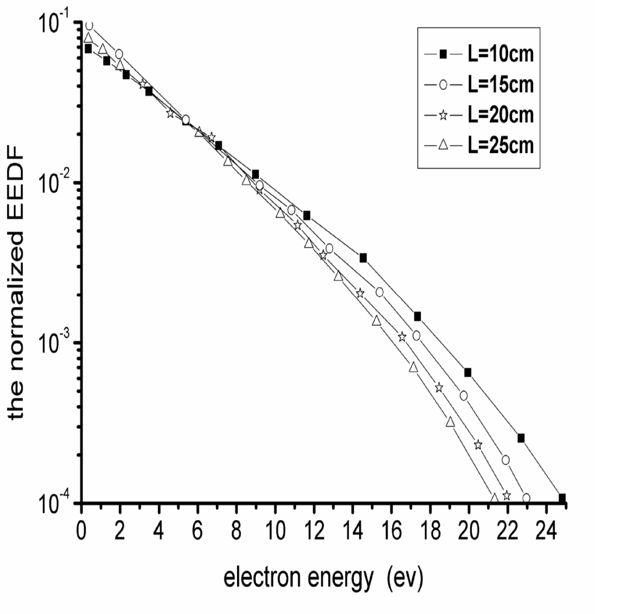


Fig.7 Influence of height of the plasma antenna on the EEDF, other parameters: $\omega=2\pi\times13.56$MHz, I=10A,P=15p, n=1, R=2cm

Firstly, the analysis of effect of excitation power on the EEDF of the plasma is made. Fig.5 illustrates the influence of gas pressure on the EEDF, the frequency of excited power is 13.56 MHz and the gas pressure of plasma antenna is different. Along with the changes of frequency, discharge gas pressure of the plasma antenna is 15pa, as illustrated in the Fig.6. It can be seen that with the decrease of gas pressure and increase of discharge frequency, the number of high-energy electrons is increased gradually. The distribution of electronic energy presents Maxwell distribution and these results are consistent with the related plasma research conclusions.

The influence of length and radius of plasma antenna on the electronic energy distribution function are as shown in Fig.7 and Fig.8. It is indicated that when the length or the radius of plasma antenna increase while other parameters are constant, the electron energy will be reduced simultaneously, and the effects of radius are more apparent than the effects of plasma length as schematically shown in Fig.7 and Fig.8. So the radius of plasma antenna has a greater influence on the plasma state, and it has been verified through the related experiment s of the plasma antenna.

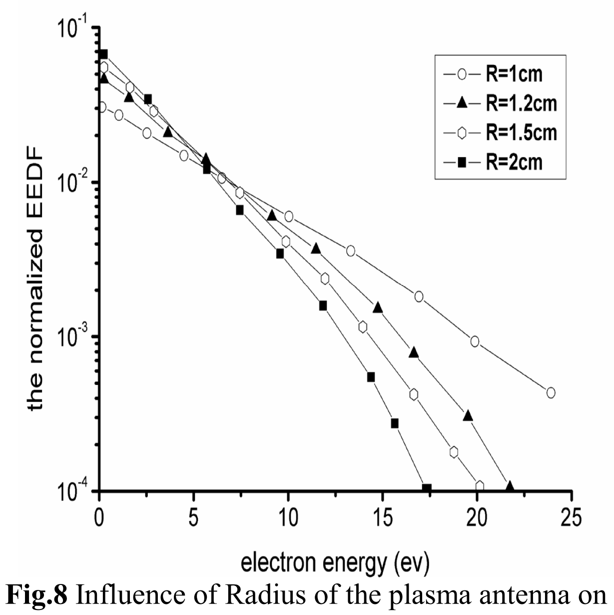


Fig.8 Influence of Radius of the plasma antenna on the EEDF, other parameters: $\omega=2\pi\times13.56$MHz, P=15Pa,I=10A, n =1, L =10cm

The strength of current in the RF coil reflects the external excitation power directly, and it determines the power coupled into plasma antenna. As shown in Fig.9, Fig.10, the EEDF changes with the strength of current in the coil. When the current of coil and the number of coil increase, the electron energy will increase accordingly.

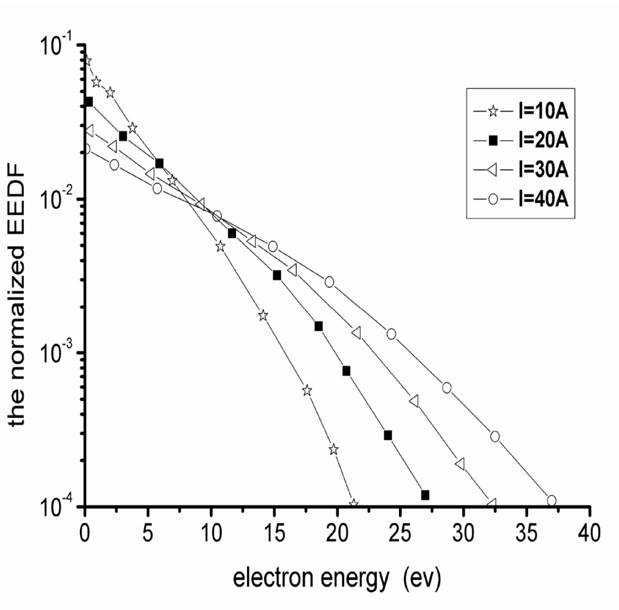


Fig.9 Influence of RF current amplitude of the plasma antenna on the EEDF, other parameters: $\omega=2\pi\times13.56$MHz, P=15Pa,R=1cm, L=10cm

Because the increase of excitation power will leads to the increase of absorption power in plasma, therefore, the state of plasma can be controlled through changing the number of coils and RF currents in coupling coils.

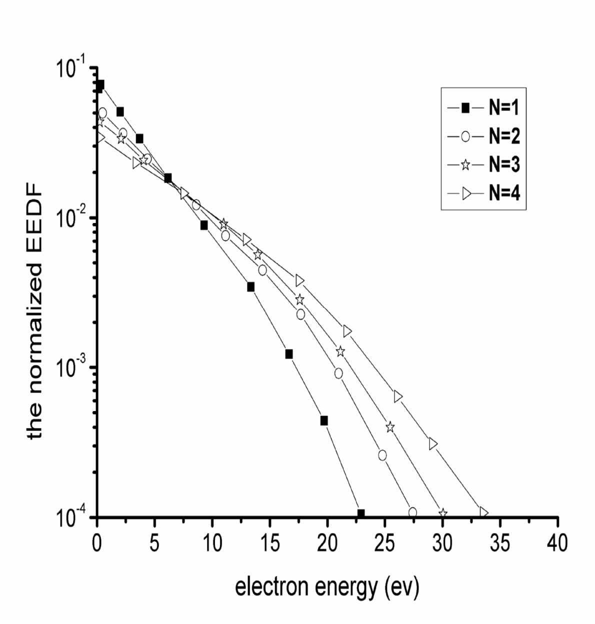


Fig.10 Influence of turns number of the plasma antenna on the EEDF, other parameters: $\omega=2\pi\times13.56$MHz, P=15Pa, R=1cm, L=10cm

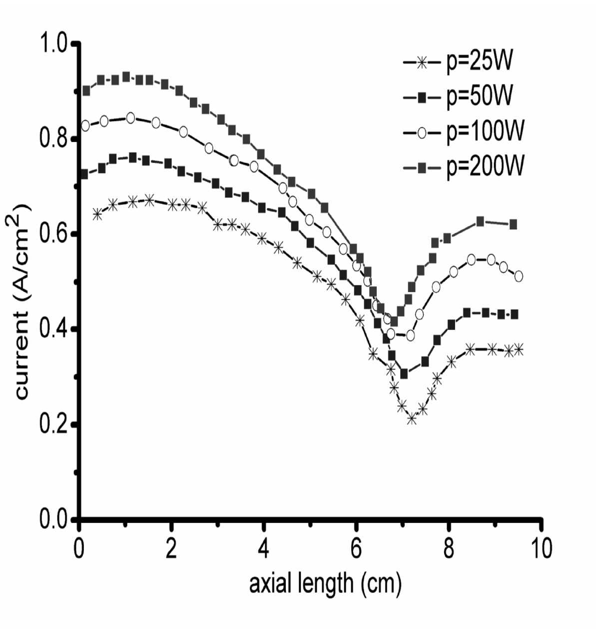


Fig.11 Experiment results of surface current of the Plasma Antenna

The measurement results of the plasma antenna experiments are shown as Fig.11, Fig.12, and from figures above we can find that the experiment results present the same tendency as the numerical simulation results of the three-dimensional model. If we compare the numerical simulation results with the measure results of experiments in the Fig.11, Fig.12, Fig.13 and Fig.14, we can conclude that three-dimensional model can be used in control and predication of the monopole plasma antenna.

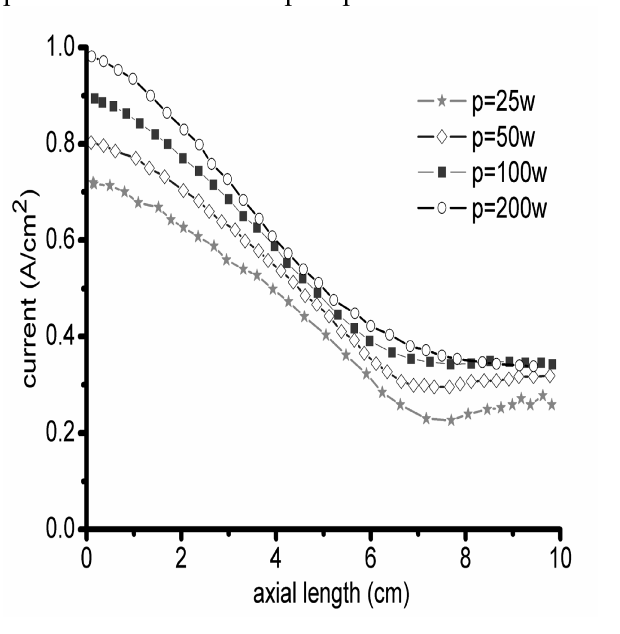


Fig.12 Model calculation results of surface current of the plasma antenna

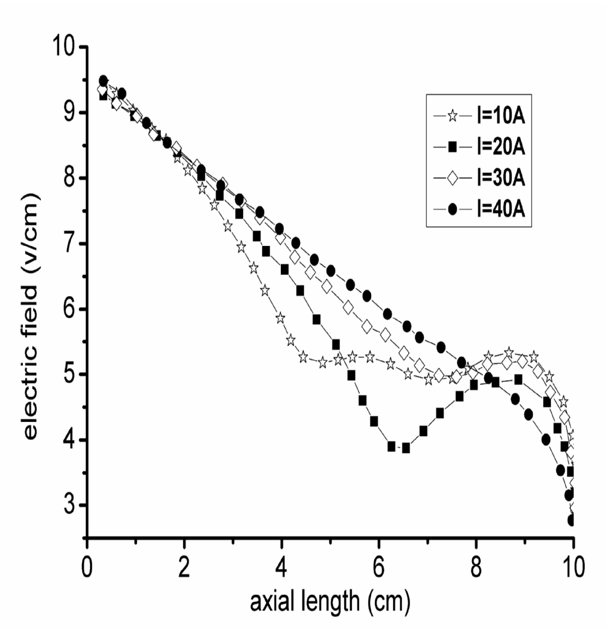


Fig.13 Experiment results of electric field around the plasma antenna

We have analyzed EEDF of cylindrical monopole plasma antenna excited by surface wave above, and the relationships between EEDF and gas pressure, radius of antenna, coupling method and external excited field through numerical simulation method. Through the analysis of numerical results and experiments results, the calculation results of the model can reflect the electromagnetic field distribution around the antenna as well as the distribution characteristics of power density and surface current.

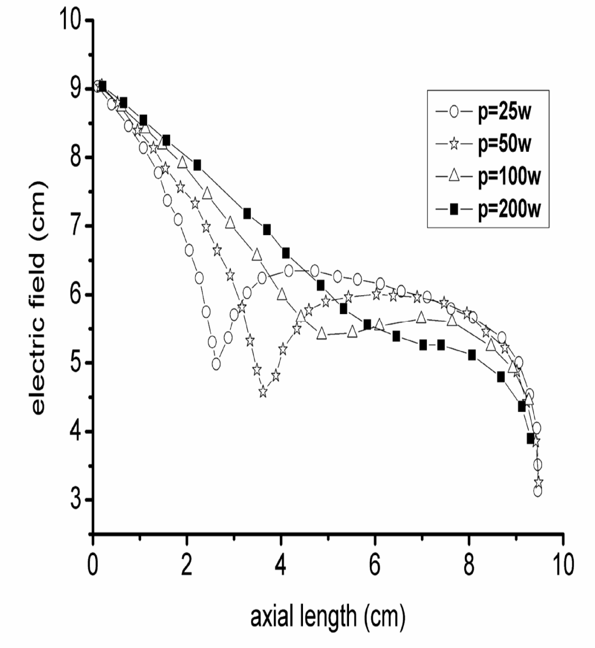


Fig.14 Calculation results of electric field around the plasma antenna

5 Conclusion

The three-dimensional model proposed in the paper can present a qualitative guidance for the plasma antenna research, but the electrostatic field distribution in the plasma and the effect of sheath layer around inside the antenna are not taken into consideration. So if the researchers want to make more precise analysis and prediction of the plasma antenna, a more reasonable multi-dimensional model should be put forward.

Acknowledgement

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