Microwave interference diagnosis of plasma based on fluid dynamics modeling

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Abstract. Aim at the problem that microwave interference diagnosis of plasma can only get an average electron density along the transmission path of microwave, this paper put forward a new microwave interference diagnosis method based on fluid dynamics modelling to gain accurate distribution of electron density. In this method, the fluid model of inductively coupled plasma (ICP) is set up by multi-physics coupling method on COMSOL platform. Then a group of Boltzmann equations is introduced to solve the electron energy distribution function (EEDF), diffusion coefficient and transport coefficient. Based on the fluid dynamics model, the bivariate distribution of electron density is obtained by solving the electron drift diffusion equations, electron energy drift diffusion equations and momentum flux conservation equations. Then the profile function of electron density along the transmission path of microwave can be collected from it. And the profile function is discretized to make it easier to calculate the electron density of different parts. At last, an experiment system of ICP in transparent chamber is set up to verify the effectiveness of the new method. The electron density is diagnosed by the new microwave interference diagnosis and Langmuir probe respectively. The results reveal that the electron density rises with power and the peak value can reach $7.8 \times 10^{17}$ m$^{-3}$ at the radio frequency (RF) power of 700 W. The new method makes up for the deficiencies of traditional microwave interference diagnosis and numerical simulation effectively.

1. Introduction

Thanks to the advantages of high electron density, steady state of discharge and easy to be conformal to aircraft surface, inductively coupled plasma (ICP) in closed chamber is very appropriate for stealth design of aircraft local, such as inlet duct, wing leading edges and radar cabin. The performance to attenuate electromagnetic wave of plasma is closely related to electron density. So diagnosis technique of plasma electron density is one of the critical foundations of plasma stealth technology.

There are many diagnosis methods of plasma electron density, for example, probe diagnosis, spectral diagnosis, wave interference diagnosis and so on. Probe diagnosis is precise and simple. But inserting the probe into plasma will have a disturbing effect. Compared with it, spectral diagnosis and wave interference diagnosis are both non-intrusive and barely produce interference. However, the inaccuracy and great many calculations prevent the wide application of spectral diagnosis. Wave interference diagnosis, although is accurate relatively, but can only get an average electron density along the transmission path of microwave due to the restriction of wave length and plasma dimension. For example, the E-H mode transition of a kind of irregular spiral ICP in interlayer chamber was studied in reference [1]. The electron density was diagnosed using microwave interference method,
but only an average range of electron density was got. No distribution details were involved. The
electron density of a planar ICP was diagnosed using Langmuir probe and microwave interference in
reference [2]. Comprehensive analysis indicated that the radio frequency (RF) component of ICP
would produce definite interference to probe. In reference [3], the relation of electron density,
collision free path and collision frequency in large planar ICP antenna with pressure was studied, but
no quantitative diagnosis of electron density was involved.

Numerical simulation of plasma can greatly help analysing plasma characters [4]. But error always
exists in simulation because various power losses are not considered. In this paper, a new microwave
interference diagnosis method based on fluid dynamics modeling is presented in allusion to the
particular structure of ICP in wave-transmissible chamber. Through combining numerical simulation
with microwave interference, the new method decreases error and improves spatial resolution ratio of
electron density effectively.

2. Fluid dynamics model
Fluid dynamics model [5] is one of the often-used numerical simulating methods of non-thermal
plasma. In this model, collision is simplified due to the use of iterative feedback progress of Particle in
Cell (PIC) like Monte Carlo method. Moreover, the particles distribution functions are described by
simple hypothetical functions so that computational expense is reduced. However, because some
details in experiment such as reflected power are ignored, the simulated result is not very exact. Thus,
it is undependable for quantificational calculation. Even so, the spatial distribution trend of plasma
parameters can be given. That is enough for the microwave interference diagnosis based on fluid
dynamics modeling in this paper.

The calculation in fluid dynamics model is based on the following assumptions. First, the influence
of magnetic field on electron motion is not considered. Second, the electric field is steady and
homogeneous within the mean collision free path. Third, the electron distribution function obeys axis
symmetric distribution and varies only in the direction of electric field. Fourth, elastic collision is the
dominating collision. Fifth, for ICP discharging model axisymmetric in planar surface, the RF
magnetic field distributes merely in the r-z plane when only the inductive mode is considered. And the
electric field exists merely in θ direction.

2.1. The electron energy distribution function (EEDF)
In fluid dynamics model, EEDF will influence the non-balance of plasma discharging. This is
generally solved by making an assumption of EEDF in advance. Maxwell distribution is often used.
But in low pressure which is the usual discharging condition of ICP, EEDF will diverge from Maxwell
distribution because of the influence of electron non-locality, constraint of bipolar barrier and
Ramsauer effect. In this case, the assumption is inaccurate and not dependable. Accordingly,
Boltzmann equations are introduced in this paper. So the EEDF, the electron transport coefficient,
diffusion coefficient and the rate coefficient of electron collision reaction can be solved.

In fluid dynamics model, the spatial distribution of ion and neutral particle is mainly described by
Boltzmann equations. The quantitative variation of electron contained in six-dimensional volume
element can be described by the six-dimensional phase space distribution function \( f(r, v, t) \). The
Boltzmann equations of electron can be expressed as [6]:

\[
\iiint f(r, v, t) dv = n_e
\]

\[
\frac{\partial f}{\partial t} + v \cdot \nabla f - \frac{e}{m_e} E \cdot \nabla_v f = C[f]
\]

Where \( v \) is the velocity coordinates. \( n_e \) is the electron density. \( e \) is the electron charge. \( m_e \) is the
electron mass. \( E \) is the intensity of electric field. \( \nabla V \) is the velocity-gradient operator. \( C[f] \) represents
the rate of change in \( f \) due to collisions.
The Boltzmann equation can be indicated as follows in cylindrical-coordinate system with velocity of \( v \) [7].

\[
\frac{\partial f}{\partial t} + v \cos \theta \frac{\partial f}{\partial z} - \frac{e}{m_e} E \left( \cos \theta \frac{\partial f}{\partial v} + \frac{\sin^2 \theta}{v} \frac{\partial f}{\partial \cos \theta} \right) = C[f]
\]

(3)

\[
f(v, \cos \theta, z, t) = f_0(v, z, t) + f_1(v, z, t) \cos \theta e^{j \omega t}
\]

(4)

Where \( \theta \) is the angle between the electron velocity and the direction of electric field, and \( z \) is the position along this direction. The distribution function \( f(r, v, t) \) in rectangular coordinate system is revised as \( f(v, \cos \theta, z, t) \). And \( f(v, \cos \theta, z, t) \) can be expanded as equation (4). The isotropic term \( f_0(v, z, t) \) represents the isotropic velocity and the anisotropic term \( f_1(v, z, t) \cos \theta \) represents the anisotropic velocity. \( e^{j \omega t} \) is the modification term of RF discharge. For unmagnetized plasma, \( \theta \) is the direction of electric field. \( f_0 \) and \( f_1 \) can be deduced from equation (3) by substituting equation (4) and multiplying by the respective Legendre polynomial \((1, \cos \theta)\) and integrated over \( \cos \theta \).

\[
\frac{\partial f_0}{\partial t} + \frac{\gamma_e}{3} \frac{\partial f_0}{\partial \varepsilon} - \frac{\gamma_e}{3} \varepsilon^{1/2} \frac{\partial}{\partial \varepsilon} (\varepsilon E f_1) = C_0
\]

(5)

\[
\frac{\partial f_1}{\partial t} + \varepsilon^{1/2} \frac{\partial f_0}{\partial \varepsilon} - E \varepsilon^{1/2} \frac{\partial f_0}{\partial \varepsilon} = -N \sigma_m \varepsilon^{1/2} f_1
\]

(6)

Here \( \gamma_e = (2e/m_e)^{1/2} \) is constant. \( \varepsilon = (v/\gamma_e)^2 \) is the electron energy. \( C_0 \) is collision term which represents the energy loss due to elastic collisions. \( N \) is the gas density. \( \sigma_m \) is the total momentum-transfer cross-section consisting of contributions from all possible collision processes \( j \) with neutral particles.

\[
\sigma_m = \sum_j x_j \sigma_j
\]

(7)

Where \( x_j \) is the mole fraction of certain particle for reaction \( j \). \( \sigma_j \) is the effective momentum-transfer cross-section. For elastic collision, \( \sigma_j \) is the sum of anisotropy in elastic scattering. For inelastic collision, \( \sigma_j \) is the total collision cross-section, i.e. that the remaining electron velocity after collision is scattered isotropically.

To solve \( f_0(v, z, t) \) and \( f_1(v, z, t) \), separate the energy-dependence \( f_{0,1}(\varepsilon, z, t) \) from its dependence on time domain and space domain by assuming that

\[
f_{0,1}(\varepsilon, z, t) = \frac{1}{2\pi\gamma} F_{0,1}(\varepsilon) n_e(z, t)
\]

(8)

Where the energy distribution \( F_{0,1} \) is constant in time and space and normalized by

\[
\int_0^{\infty} \varepsilon^{1/2} F_0 d\varepsilon = 1
\]

(9)

Usually the frequency of ICP discharge is 13.56 MHz. The transfer energy in one single period can not be ignored. In stable inductive discharging, the increase of electron density \( n_e(z, t) \) is the function of time and space. Then equation (5) and (6) could be turned into

\[
F_i = \frac{E_0}{N} \frac{\gamma_e}{\sigma_m} \left( \frac{\gamma_e}{N} \right) \frac{\partial F_0}{\partial \varepsilon} + \frac{\partial}{\partial \varepsilon} \left( \frac{\frac{\gamma_e}{N} \sigma_m \varepsilon}{\sigma_m + \left( \frac{\gamma_e}{N} \right)^2} \right) \frac{\partial F_0}{\partial \varepsilon} \frac{\partial F_0}{\partial \varepsilon} = \tilde{C}_0 + \tilde{R}
\]

(11)
\[ \hat{\sigma}_m = \sigma_m + \frac{\rho}{N_\gamma e^{1/2}} \]  

(12)

The net electron production \( \rho \) is related to a constant spatial growth rate \( \eta \).

\[ \rho = -\frac{\tau}{n} \frac{\partial n}{\partial z} = -\eta \tau \]  

(13)

\( \tau \) is the mean velocity which determined by \( F_1 \), constant in space and negative.

\[ \tau = \frac{1}{3} \gamma \int_0^\infty F_0 \varepsilon d\varepsilon \]  

(14)

The collision term is

\[ \tilde{C}_0 = 2 \pi \gamma^{1/2} \frac{C_0}{Nn} \]  

(15)

The growth-renormalization term \( \tilde{R} \) ensures that \( F_0 \) remains normalized to unity in the case of net electron production.

\[ \tilde{R} = -\frac{P}{N} \varepsilon^{1/2} F_0 \]  

(16)

When combining the above equations, \( F_0 \) can be obtained by solving the convection-diffusion continuity-equation in energy space [8].

\[ \frac{\partial}{\partial \varepsilon} \left( WF_0 - D \frac{\partial F_0}{\partial \varepsilon} \right) = S \]  

(17)

Where \( W \) is the negative flow velocity in convective diffusion, representing the attenuation of convective diffusion due to elastic collision with less energetic particles. \( D \) is the diffusion coefficient, which represents the energy transfer caused by field heating and elastic collision with more energetic particles. \( S \) is the source term.

In cylindrical-coordinate system, the isotropy item in \( f (v, \cos \theta, z, t) \) makes no contributions to electricity. The continuity equation for electron can be obtained from equation (5) and (6) by multiplying by \( e^{1/2} \) and integrating over all energies:

\[ \frac{\partial n}{\partial t} + \frac{\partial \Gamma_e}{\partial z} = S_e \]  

(18)

Where \( S_e \) is the net electron source term and \( \Gamma_e \) is the electron flux.

\[ \Gamma_e = n \frac{1}{3} \int_0^\infty \varepsilon F_0 d\varepsilon \]  

(19)

The well-known drift-diffusion equation of electron can be got from this and equation (6). And the drift-diffusion equation of electron energy can be got through the same analyzing process. The mobility rate \( \mu_e \) and diffusion coefficient \( D_e \) of electron and mobility rate \( \mu_\varepsilon \) and diffusion coefficient \( D_\varepsilon \) of electron energy are as follows.

\[ \mu_e N = \frac{1}{3} \int_0^\infty \frac{\varepsilon}{\hat{\sigma}_m} \frac{\partial F_0}{\partial \varepsilon} d\varepsilon \]  

(20)
Based on the above analysis, the EEDF of Argon (Ar) ICP under 10 mTorr solved by Boltzmann equations is shown in figure 1. The collision scattering section of Ar is obtained in reference [9]. For Ar under 10 mTorr, low-energy electron is restrained by the bipolar potential well. The main component participating in the heating process is medium-energy electron. So it is seen in figure 1 that the EEDF at the center of the chamber presents a double Maxwell distribution. And in low-energy area, the power has little influence on the EEDF. The electron energy rises with power in heating area, so the trailing area of high energy extends continually with power increasing. In the area near the coil, plasma locates in the heating area and the ionization degree is low, so the trailing area extends.

![Figure 1. The EEDF of different power.](image1)

![Figure 2. The fluid dynamics model in COMSOL.](image2)

2.2. The distribution of $n_e$

Now the EEDF is obtained, the distribution of $n_e$ can be solved by fluid dynamics modeling. As is shown in figure 2, the fluid dynamics model is set up in the plasma fluid module of COMSOL Multiphysics platform and solved in frequency domain. The coil antenna is set as hollow brass pipe with the diameter of 8 mm. To realize the process of electromagnetic energy coupled into plasma, the initial electron density $n_{e0}$ and initial average electron energy $\varepsilon_0$ must be set in advance. Logical initial conditions are conducive to boost the iteration of model. After calculation, $n_{e0}$ is set as $10^9$ cm$^{-3}$ and $\varepsilon_0$ is 5 eV. The temperature is 297 K. The working gas is Ar. The coil antenna is in power drive mode and the power is in accordance with the forward power of the corresponding experiment in section 4. The model is generated into free triangular meshes. The size of the meshes is between $1.75 \times 10^{-2}$ mm to 5.18 mm. And near the boundary, the max is less than 1 mm. At last, 52068 meshes are generated.

The dynamics behaviour of electron is described by electron continuity equation, momentum conservation equation and electronic energy density equation [10].

$$\frac{\partial n_e}{\partial t} + \nabla \cdot \Gamma_e + E \cdot \Gamma_e = R_e$$  

$$\frac{\partial (n_e \mu_e)}{\partial t} + \nabla \cdot n_e \mu_e \tau = - (\nabla \cdot \rho_e) + q n_e E - n_e \mu_e \nabla \varepsilon_m$$
Where $\Gamma_e$ is the electronic energy flux density. The electron source $R_e$ and energy loss due to inelastic collision $R_\varepsilon$ will be defined later. $p_e$ is the stress tensor of electron. $q$ is the variation of electron charge. $n_\varepsilon$ is the electronic energy density. $u$ is the velocity of neutral gas. $v_m$ is the collision frequency and is defined as:

$$v_m = N\sigma(u)$$  \hspace{1cm} (27)

The multinomials in equation (25) are the acceleration term, the inertia term, the electric field term, the pressure gradient term and the collision term from left to right respectively. Under low pressure, the inertia term can be ignored considering that the electron drift velocity is less than the thermal velocity. Then the equation of electron drift velocity $u_e$ could be deduced from equation (25).

$$u_e = \frac{1}{n_m v_m} [- (\nabla \cdot p_e) + q n_\varepsilon E]$$  \hspace{1cm} (28)

The result is coupled into the fluid dynamics model of COMSOL in the form of differential function. So the electron flux $\Gamma_e$ and energy flux $\Gamma_\varepsilon$ can be described as:

$$\Gamma_e = n_e u_e = - (\mu_e \cdot E) n_e - \nabla (D_e n_e)$$  \hspace{1cm} (29)

$$\Gamma_\varepsilon = - (u_e \cdot E) n_e - \nabla (D_\varepsilon n_e)$$  \hspace{1cm} (30)

Where $u_e$ is the drift velocity of electron energy. The boundary conditions for electrons and electrons energy are set as equation (31) and equation (32), without considering secondary emission of electron.

$$- \beta \cdot \Gamma_e = (1/4) \cdot v_{th} \cdot n_e$$  \hspace{1cm} (31)

$$- \beta \cdot \Gamma_\varepsilon = (5/3) \cdot (v_{th} \cdot n_e) / 4$$  \hspace{1cm} (32)

Where $\beta$ is the normal to the surface and $v_{th}$ is the thermal velocity of electron. Suppose there are $P$ chemical reactions that contribute to the growth or decay of ne and $Q$ inelastic electron-neutral collisions in the plasma. In the case of rate coefficient, the electron source term is given by:

$$R_e = \sum_{j=1}^{P} x_j k_j N_n n_e$$  \hspace{1cm} (33)

And the electron energy loss is obtained by summing the collisional energy loss over all reactions.

$$R_\varepsilon = \sum_{j=1}^{Q} x_j k_j N_n n_e \Delta \varepsilon_j$$  \hspace{1cm} (34)

Where $k_j$ is the rate coefficient for reaction $j$ which can be calculated based on electron collision cross-section under the condition of discharging. $N_n$ is the total neutral number density. $\Delta \varepsilon_j$ is the energy loss from reaction $j$.

There are 20 kinds of chemical reactions involved in Ar discharging. To reduce the amount of calculating, only the main reactions adopted in reference [11] are considered. Then $k_j$ can be calculated from cross-section by the following integral of EEDF $f(\varepsilon)$.

$$k_j = \gamma_j \int_{0}^{\infty} \varepsilon \sigma_j(\varepsilon) f(\varepsilon) d\varepsilon$$  \hspace{1cm} (35)

Based on the above assumptions, only the oscillation motion in $\theta$ direction matters when solving the electron continuity equation and momentum conservation equation. Moreover, $n_e$ can be
considered uniform in $\theta$ direction because it obeys axisymmetric distribution. So the momentum conservation equation is simplified as:

$$\frac{\partial (n_e m_e u_{e,\theta})}{\partial t} = qn_e E_\theta - n_e m_e u_{e,\theta} v_m$$

(36)

In frequency domain, $E_\theta = \tilde{E}_\theta e^{j\omega t}$ and $u_{e,\theta} = \tilde{u}_{e,\theta} e^{j\omega t}$. So the plasma electric current is expressed as:

$$j = qn_e \tilde{u}_{e,\theta} = \frac{q^2 n_e}{m_e} (v_m + j\omega)$$

(37)

$$\tilde{J}_\theta = \frac{q}{n_e} \tilde{u}_{e,\theta}$$

(38)

$$E \cdot \Gamma_e = \frac{E_\theta}{q} = \frac{1}{q} \frac{1}{2} \text{real} \left( \tilde{E}_\theta \tilde{J}_\theta \right)$$

(39)

3. Microwave interference diagnosis

Because the oscillation frequency $\omega_p$ of non-thermal plasma is in the frequency band of microwave, amplitude attenuations and phase shifts will be produced when microwave propagates in non-thermal plasma. In microwave interference diagnosis, the effective permittivity of plasma is calculated by measuring the phase shift, and then the electron density can be obtained.

The plasma microwave interference diagnosis system is shown in figure 3. Microwave generated from the microwave vector network analyser (VNA) is transmitted by the transmitting-receiving community horn antenna. The wave travels through the plasma and is reflected by the metal reflector back of the plasma. Then the wave passes across the plasma again and back to the VNA through the horn antenna. The phase shift $\Delta \varphi$ is calculated in the VNA by comparing the return wave with the forward wave.

![Figure 3. The microwave interference diagnosis system.](image)

The influence of collision to $\Delta \varphi$ can be ignored when the plasma pressure is between 10 mTorr to 1 Torr. $\Delta \varphi$ can be indicated as the line integral over $n_e$ along the transmission path of microwave.

$$\Delta \varphi = k_0 \int_0^l \left[ 1 - \frac{\omega_p^2 (x)}{\omega^2} \right]^{1/2} dx$$

(40)

Where $k_0$ is the Boltzmann constant, $\omega$ is the frequency of microwave. $\omega_p$ is the plasma frequency. $l$ is the length of the microwave transmission path. $\epsilon_0$ is permittivity of air. $\pi_e$ is the average value of $n_e$ along the transmission path of microwave.

It is easy to get $\Delta \varphi$ by solving equation (38) [12]. But to get the distribution detail of $n_e$, the profile function of $n_e$ must be obtained in advance. One method is solving the diffusion equations in steady state and using the solution as an approximation of the profile function [13]. But it is quite difficult to solve the diffusion equations under different conditions. Moreover, this kind of constant profile function can not reflect the influences of external factors to the distribution of $n_e$. 


As is described in section 2, by means of simulated calculation in fluid dynamics model, the bivariate distribution of $n_e$ is obtained. And the profile function of $n_e$ along the transmission path of microwave can be collected from it. And next, the profilogram of the profile function is discretized to make it easier to calculate the electron density of different parts. As is shown in figure 4, $M$ is the discretizing number. $\Delta l (\Delta l = l/M)$ is the width of every discretized section.

Define $\alpha_i = n_{e-i} / n_{e-max}$ as the discretization coefficient. Here $n_{e-i}$ is the electron density of the $i$th section and $n_{e-max}$ is the peak electron density of numerical simulation. So the distribution of $n_e$ can be calculated from the following equations.

$$\Delta \phi = \frac{k_0 e^2}{2 \varepsilon_0 m_e} \sum_0^M \alpha_i \cdot n'_{e,max} \cdot \Delta l$$

$$n'_{e-max} = \frac{2 \varepsilon_0 m_e \omega^2 \Delta \phi}{k_0 e^2 \Delta l} \left( \sum_0^M \alpha_i \right)^{-1}$$

$$n'_{e-i} = \alpha_i \cdot n'_{e-max}$$

Where $n'_{e-max}$ and $n'_{e-i}$ are respectively the actual value of peak electron density and density of the $i$th section along the transmission path of microwave.

4. Verification by experiment

4.1. Experiment setting
To verify the new method, an experiment of low-pressure ICP in closed chamber is conducted as shown in figure 3. The actual photo of the ICP chamber is shown in figure 5. The coil antenna is wined with hollow brass pipe whose diameter is 8 mm. Water flows in the pipe to cool the antenna. The antenna is actuated by the RF power (RSG-1000) at the frequency of 13.56 MHz. A capacitance matcher (PSG-II A) is installed between the power and antenna to ensure the reflected power less than 10 W. The chamber is a cylinder with the diameter (r direction) of 22 cm and the height (z direction) of 8 cm. The sidewall of the cylinder connected to ground is stainless steel, and the round sides of the cylinder are transparent quartz. High-purity Ar (99.99%) is filled into the chamber from a high-pressure steel bottle. A vacuum pump is used to maintain the low pressure in the chamber. Pressure in the chamber is set as 10 mTorr. A probe diagnosis system (MMLAB-probe-1) is installed to measure the electron density for comparison. By means of L-shaped probe and the expansion link, it can measure the electron density of different parts in the chamber. The microwave interference diagnosis system includes the VNA (Anritsu MS4640B) and the transceiver horn antenna. To shield interference of outer environment, all the facilities are out of the anechoic chamber except the chamber and horn antenna.
4.2. Result and discussion
According to the numerical simulation of fluid dynamics modeling, the bivariate distribution of $n_e$ is obtained and shown in figure 6. Then the discretization coefficient $\alpha_i$ is obtained by sampling from the profile function of $n_e$ as mentioned in section 3. At the frequency of 18 GHz, the phase shift measured in experiment is $\Delta \varphi = 32.4^\circ$. According to the previous descriptions in section 3, the electron density in $z$ direction by the new microwave interference diagnosis is solved and shown in figure 7.

![Figure 6. The bivariate distribution of $n_e$ by numerical simulation.](image)

![Figure 7. Comparison of $n_e$ in $z$ direction.](image)

For comparison, the results of numerical simulation and Langmuir probe are also presented in the same figure. As can be seen, $n_e$ of microwave interference is higher than that of probe and lower than simulation. But all the results are in good agreement in distribution trend. The error between probe diagnosis and the microwave interference method is less than 5%. It is believed that the microwave interference diagnosis is more exact than probe in other literatures studying the differences of the two methods [14]. Because the power loss of reflected power and capacitive component are ignored, the simulation result is 10% to 60% higher than the measured data. So it is believed that the result of microwave interference diagnosis based on fluid dynamics modeling is the most dependable and the effectiveness of the new microwave interference diagnosis is verified robustly.

It can be seen from figure 7 that the peak value of $n_e$ reaches $7.8 \times 10^{17} \text{ m}^{-3}$ at the power of 700 W. The distribution of $n_e$ is approximatively symmetrical but not absolutely. $n_e$ near the coil antenna ($0 \text{ m} < z < 0.04 \text{ m}$) is a little higher than the other side ($0.04 \text{ m} < z < 0.08 \text{ m}$). This is because electron obtains more energy in the heating area near the antenna.

And the increase of $n_e$ is nearly in direct proportion to power. It can be explained as follows. First, the increase of power directly enhances the efficiency of electron obtaining energy from skin layer. And then the ohmic heating is intensified and the ionization degree is increased. Second, higher power leads to fiercer collision between electron and neutral particle. This process will create more free electron. Third, higher power and increasing electron density reduces the proportion of capacitive component in total coupled power. Then the general coupling efficiency is improved.

Although higher power can increase the electron density, power almost has no effects on the spatial distribution of $n_e$. This is because the distribution of $n_e$ in non-thermal plasma is mainly determined by diffusion and transport under low pressure. While power has little influence on the diffusion and transport of electron in space.

5. Conclusions
A new microwave interference diagnosis method based on fluid dynamics modeling is presented in allusion to the particular structure of ICP in wave-transmissible chamber. Compared with traditional microwave interference diagnosis, the new method makes applicability more extensive. And through combining numerical modeling with microwave interference, the new method decreases the error of numerical simulation and solves the problem that traditional microwave interference diagnosis can
only get an average electron density along the transmission path of microwave. The electron density is diagnosed by the new microwave interference method and Langmuir probe respectively in an ICP discharging experiment. The consistency in the results from two methods illustrates that the new method can give a relatively accurate spatial distribution detail of electron density. The electron density rises with power and the peak value which appears in the centre of the chamber can reach 7.8×10¹⁷ m⁻³ at the RF power of 700 W.

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References
[1] Du Y C, Cao J X, W Ji, Zheng Z, Liu Y, Meng G, Ren A M and Zhang S J 2012 Mode transition of inductively coupled plasma in interlayer chamber Acta Physica Sinica 61 195-206
[2] M Andrasch, J Ehlebeck, R Foest and K-D Weltmann 2012 Electron density measurements on inductively coupled plasma with a one-port microwave interferometer Plasma Sources Science and Technology 21 055-032
[3] Di X L, Xin Y and Ning Z Y 2006 Effect of antenna configuration on power transfer efficiency for planar inductively coupled plasmas Acta Physica Sinica 55 5311-5317
[4] Yuan Z C, Shi J M, Huang Y and Ma L 2008 Analysis and comparison of numerical simulation methods of low temperature plasma Nuclear Fusion and Plasma Physics 28 278-284
[5] Herrebout D, Bogaerts A and Gijbels R 2003 A one-dimensional fluid model for an acetylene RF discharge: a study of the plasma chemistry IEEE transaction on plasma science 31 659-664
[6] John B, R O Jung, Chun C, L E Aneskavich and A E Wendt 2011 Optical diagnostics for characterization of electron energy distribution: argon inductively coupled plasmas Plasma Sources Science and Technology 20 055-006
[7] G J M Hagelaar and L C Pitchford 2005 Solving the Boltzmann equation to obtain electron transport coefficients and rate coefficients for fluid models Plasma Sources Science and Technology 14 722-733
[8] S Mouchtouris and G Dokkoris Lampton 2016 A hybrid model for low pressure inductively coupled plasmas combining a fluid model for electrons with a plasma-potential-dependent energy distribution and a fluid-Monte Carlo model for ions Plasma Sources Science and Technology 25 025-007
[9] Angel Ochoa Brezmes and Cornelia Breitkopf 2014 Simulation of inductively coupled plasma with applied bias voltage using COMSOL Vacuum 109 52-60
[10] Zhang W 2013 The Fluid Simulation of Argon Discharge and Its Verification with COMSOL Software (Da Lian: Da Lian University of Technology)
[11] Angel Ochoa Brezmes and Cornelia Breitkopf 2015 Fast and reliable simulation of argon inductively coupled plasma using COMSOL Vacuum 116 65-72
[12] C H Chang, C H Hsieh, H T Wang, J Y Jeng, K C Leou and C Lin 2007 A transmission-line microwave interferometer for plasma electron density measurement Plasma Sources Science and Technology 16 67-71
[13] Lieberman M A and Lichtenberg A J 2005 Principles of Plasma Discharges and Materials Processing (New York: Wiley)
[14] V I Kolobov and V A Godyak 1992 Nonlocal electron kinetics in collisional gas discharge plasmas IEEE Transactions on plasma science 23 5037-5531