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AN APPLICATION OF MICROWAVES REFRACTION FOR INHOMOGENEOUS PLASMA DIAGNOSTIC

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A brief review of the main microwave diagnostics methods of inhomogeneous plasma based on the refraction of microwaves is given. These methods make it possible to determine the plasma density distribution, the magnetic field distribution, the electron collision frequency, and the electron temperature profile. In addition, the determination of the average density of the peripheral plasma layers and the local inhomogeneities of the rotating plasma are also possible. The effect of refraction on the accuracy of determining the plasma parameters by using microwave methods for plasma diagnostics is considered.

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INTRODUCTION

The development of plasma physics and progress in the study of space and laboratory plasma, including fusion devices plasma are substantially determined by the development of the methods for measuring its parameters. In modern research, in the field of plasma physics, a quite wide range of methods are used for plasma diagnostic, such as [1-3]: probe, optical and spectral, laser, microwave, corpuscular.

Non-contact methods, for example, microwave ones [1-9], are widely used in experimental studies of plasma. In passive methods, the own microwave radiation from plasma is measured. Active microwave methods are based on measuring the result of the interaction of electromagnetic waves with plasma. Active microwave methods include, for example, interferometry and plasma reflectometry. Plasma diagnostics also use methods based on the refraction of microwave rays in plasma [5, 6], which are classified as active microwave methods.

Research on the study of the possibility of using microwaves refraction for diagnostics of inhomogeneous plasma was started in the early 60s of the XX century [10]. At present, the literature on this issue is in a rather scattered form. The results of the earliest studies are partly described in the monograph [5] and the review [6], published over 45 years ago. Therefore, the purpose of this work is to generalize both the authors and the literature data on the use of microwaves refraction in inhomogeneous plasma for its diagnosis.

1. GEOMETRICAL OPTICS AND RAY TRACING

A branch of optics in which the finiteness of wavelengths is neglected, which corresponds to the passage to the limit $\lambda_0 \to 0$ (λ_0 – vacuum wavelength), is called geometric optics. Therefore, in this approximation, the optical laws can be formulated in the language of geometry [11]. Two approaches for constructing the method of geometric optics are used. The first is based on the derivation of the geometric optics equations from the wave equations, the second, the geometric optics equations are derived from the variational principle, in optics – Fermat's principle [11, 12]. Within the framework of geometric optics, light (electromagnetic waves) is considered as a beam of rays. Geometric rays are defined as trajectories orthogonal to the geometric wavefronts. The ray equation for the model of a plane stratified medium (Fig. 1,a), the refractive index of which depends on the one coordinate, has the form [12]:

$$\frac{\mathrm{d}z}{\mathrm{d}x} = \frac{\sin\Psi}{\sqrt{n^2(x) - \sin^2\Psi}}, \qquad (1)$$

where $n(x)$ is the refractive index of the medium, Ψ is the angle between the direction of propagation and the plasma layer at the point of incidence, x is the current coordinate. The ray equation in radially inhomogeneous symmetric media, namely, a cylindrically stratified medium (Fig. 1,b) has the form [12]:

$$\frac{\mathrm{d}\theta}{\mathrm{d}r} = \frac{R\sin\Psi}{\sqrt{r^2 n^2(r) - R^2\sin^2\Psi}}, \qquad (2)$$

where Ψ the angle between the beam propagation direction and the cylinder radius at the point, where the beam falls on the plasma cylinder; θ the deviation angle of the radius vector from its initial position; R the radius of the cylinder; r – current coordinate; $n(r)$ the refractive index.

Refraction is considered as a separate phenomenon independent of wave diffraction only when it is possible to apply a ray description of wave processes (in the framework of the geometric optics approximation).

Snell's law (also Snell's law), known as Snell-Descartes law, describe the relationship between the angles of incidence and refraction when referring to light or other waves passing through a boundary between two different isotropic media with different refractive indices:

$$n_1 \sin(\upsilon_1) = n_2 \sin(\upsilon_2), \qquad (3)$$

where n_1 the refractive index of the medium 1 from which the ray falls on the interface; υ_1 angle of incidence – the angle between the incident ray on the surface and the normal to the surface; n_2 is the refractive index of the medium, in which the ray propagates after passing the interface; υ_2 angle of refraction – the angle between the ray passing through the interface and the normal to the interface.

The geometrical optics approximation is used when the propagation of electromagnetic waves in plasma is considered [13]. For one-dimensional problems, the conditions for the applicability of the geometric optics approximation were considered in [13]:

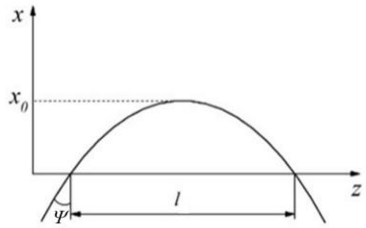
at normal incidence:

$$\frac{\lambda_0}{2\pi}\cdot\frac{\left|\frac{dn}{dz}\right|}{\left|n^2\right|} << 1, \tag{4}$$

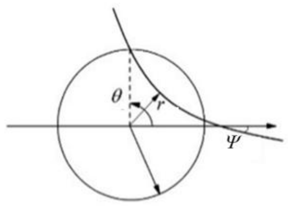
at inclined incidence:

$$\frac{\lambda_0}{2\pi}\cdot\frac{\left|\frac{d(n\cdot\cos\Psi)}{dz}\right|}{\left|n^2\cos^2\Psi\right|} << 1, \tag{5}$$

where n is the refractive index of the medium. This condition is clearly broken when $cos\Psi\rightarrow 0$, that is, when approaching the point of reflection. These conditions, in fact, are reduced to the requirement that the change in the refractive index n at the wavelength in the medium should be small.



a



b

Fig. 1. Oblique incidence of the beam on the surface: a – plane stratified medium, b – cylindrically stratified medium

2. PLASMA DIAGNOSTIC METHODS BASED ON MICROWAVE REFRACTION IN INHOMOGENEOUS PLASMA

The methods based on the refraction of microwave rays are also used in plasma diagnostics. For this, inclined probing of the plasma column should be realized [10, 14-36]. In this case, it is required to vary in a wide range the angle of inclination of the horn antennas with respect to the plasma. An important condition for the application of the method is the use of narrow microwave beams, allowing compliance with the conditions of geometric optics. Microwave methods based on refraction in inhomogeneous plasma may determine the distribution of the plasma density, the distribution of the magnetic field, the frequency of collisions of the electrons, and the electron temperature profile.

2.1. DETERMINATION OF THE PLASMA DENSITY PROFILE

The possibility of using the refraction of microwaves for plasma diagnostics, for the first time, was theoretically considered in [10]. A proposed method for determining the plasma density profile was based on inclined probing by microwaves at various angles in the plane normal to the plasma column. Expressions for the deflection angle of the microwave beam from the impact parameter were obtained analytically for the various distributions: $N(r) = N_{\max} = const$, $N(r) = N_{\max}\left[1-\left(\frac{r}{R}\right)^2\right]$, $N(r) = N_{\max}\left[1-0.5\left(\frac{r}{R}\right)^2\right]$, where $N_{\max}$ maximum plasma density.

The calculations of the microwave ray trajectory, phase shift and attenuation for the parabolic density profile, for the case, when microwaves propagate in the plane normal to the cylinder axis, were carried out in [14].

A method based on probing a plasma column with a microwave ray incident at an angle on its boundary is considered in [15]. According to this model, the determination of profile requires measurements at two angles of incidence. In this case, it is assumed that the density profile can be specified by the model functions $N(x) = N_{\max}\left(\frac{x}{r_0}\right)^{\alpha}$ and $N(x) = N_{\max}\left(\sin\frac{\pi}{2}\frac{x}{R}\right)^{\alpha}$, where α is an exponent. This method was used to study the decaying argon plasma of a linear pinch. Plasma was created in a glass chamber 300 mm in diameter and 1500 mm long. Plasma probing was carried out by microwaves with λ_0 = 8.9 and 4.3 mm along the axis of the plasma column. Horn antennas with lenses were used for probing. It was shown that this method can be used to determine the electron density profile in a linear discharge. The development of the method described in [15] was extended in [16]. In the experiments, the plasma was probed by microwaves at a 35 GHz frequency along the axis of the cylindrical pinch. For a simpler integration, the possibility of using several approximations was shown: a piecewise linear approximation or under the assumption that the profile is parabolic. It is shown that the calculation of the plasma density profile with the piecewise linear approximation is the most accurate. The limitations of this method were considered.

In [17, 18], the question of the microwave rays refraction on a plasma cylinder with the radial density distributions $N(r) = N_{\max}\left[1-\left(\frac{r}{R}\right)^{\gamma}\right]$ was considered, where $\gamma = \overline{N}/N_{\max} - \overline{N}$, $\overline{N}$ the average plasma density, which was determined by the interferometry method, when probing through the axis of the plasma cylinder. The influence of refraction on the measurements of microwave signal attenuation in plasma is also considered. An experimental study of the microwave's refraction was carried out in a hydrogen plasma of a pulsed reflex discharge in a glass chamber 100 mm in diameter. The probing was carried out by an *O*-wave with λ_0=8.2 mm across the plasma column. The maximum density was determined from the cutoffs of microwave signals with λ_0=2, 4, and 8 mm. The average plasma density was determined using an interferometer with λ_0=2 mm. It is shown that the radial density distribution function can be found from the angle of refraction if the maximum density is known.

The method of inclined probing across the plasma formation was used to determine the profile of the electron density during the afterglow of the hydrogen plasma of a linear pinch discharge [19]. The discharge was stabilized in a magnetic field. Plasma was created in a spherical chamber 700 mm in diameter. All experiments were performed at a fixed wavelength of 8.54 mm. Horn antennas with lenses were used for probing. The density profile was determined from measurements using an Abel-type equation. The method has been verified using interferometric measurements.

Methods for determining the plasma density profile using refraction with an arbitrary density distribution were considered in [20, 21]. In the model of plane stratified medium (see Fig. 1,a), integrating equation 1, we find the distance between the entry and reemerge points of the beam from the plasma [21]:

$$l(\Psi) = 2\int_0^{x_0} \frac{\sin\Psi \,\mathrm{dx}}{\sqrt{n^2(x) - \sin^2\Psi}}, \qquad (6)$$

where x_0 is the turning point of a ray trajectory, which is determined from the condition: $\sin^2\Psi = n^2(x)$. Equation (6) is reduced to an integral equation of the Abel type, the solution of which has the form [21]:

$$x = \frac{1}{\pi}\int_{\sqrt{n^2(x)}}^{1} \frac{l(\Psi)\cdot \mathrm{d}\sin\Psi}{\sqrt{\sin^2\Psi - n^2(x)}}. \qquad (7)$$

This equation determines (implicitly) the dependence $n=n(x)$ according to the well-known relation $l = l(\Psi)$. If the dependence of the beam emerge points from the plasma on the angle of incidence $l(\Psi)$ have been obtained from the experiments, the radial dependence of the refractive index can be found. From which it is easy to determine the density distribution.

In a cylindrically stratified medium (see Fig. 1,b), the deviation angle of the radius vector from its initial position at the entrance to the plasma can be determined by integrating equation (2) [21]:

$$\theta(\Psi) = 2R\sin\Psi \int_R^{r_0} \frac{dr}{r^2\sqrt{n^2(r) - \frac{R^2}{r^2}\sin^2\Psi}}, \qquad (8)$$

where r_0 is the turning point of a ray trajectory, which is determined from the condition: $\frac{R^2}{r^2}\sin^2\Psi = n^2(r)$. In this case, equation (8) is also reduced to an integral equation of the Abel type, the solution of which has the form [21]:

$$r = R\cdot exp\left[-\frac{1}{\pi}\int_{\sqrt{u}}^{1} \frac{\theta(\Psi) d\sin\Psi}{\sqrt{\sin^2\Psi - u}}\right], \qquad (9)$$

where $u = n^2(r)\frac{r^2}{R^2}$. This equation determines (implicitly) the dependence $n=n(r)$. The density distribution is determined from the radial dependence of the refractive index.

The approbation of the proposed technique [20, 21] for the plasma density profile studying was carried out on the decay of a hydrogen plasma formed by an electrodeless inductive discharge [22-24]. The glass chamber was 100 mm in diameter and 2000 mm long. In the described experiments, the frequency of the microwave signal was fixed λ_0=8 mm, the angle of incidence was changed. Horn antennas with dielectric plano-convex lenses were used for transmitting and probing plasma by microwaves. Comparison of the obtained density profile by probing along and across the plasma column was performed. The processing of the measurement results was carried out according to the technique [20, 21] and [15]. The measurement results were in satisfactory agreement.

The experiments on the determination of the plasma density profile using the refraction of microwave beams at different frequencies were carried out in [24, 25]. The experiments were carried out in a hydrogen plasma of a pulsed inductive discharge. Plasma was probed simultaneously using 2, 4, and 8 mm waves along and across the plasma cylinder at a fixed angle of incidence at the stage of plasma decay. So, if you set a constant angle of incidence and probe the plasma with different frequencies, the maximum density in the layer must not exceed the critical density for the highest probing frequency. The use of several microwave beams with different frequencies in the experiment makes it possible to find the density distribution at a fixed angle of incidence and to expand the boundaries of the measured density.

The determination of the plasma density profile using the refraction of microwaves was carried out on HYBTOK tokamak [26]. The electron density profile was determined during the time period when the plasma density was close to critical. Plasma was probed by waves at 70 GHz frequency. The transmitted microwave signals through the plasma were registered. These signals contained information on plasma parameters. The calculated trajectories of microwave rays are compared with experimental data. The resulting profile is consistent with the profile estimated from interferometric measurements.

A comparison of various methods for determining the plasma density profile was carried out in [27]. The density distribution was measured in a pulsed reflex discharge in a cylindrical glass chamber 1300 mm long and 90 mm in diameter in a hydrogen atmosphere. To obtain more reliable results, measurements were carried out in one cross-section of the discharge tube. The measurements showed that the plasma density profiles determined by the reflectometry method, probe, by the refraction of microwaves, by the attenuation of microwaves, are in satisfactory agreement.

In [28], it was proposed to use multiple reflections of an obliquely incident microwave beam between the critical plasma layer and the wall of the discharge chamber for plasma diagnostics.

The problem of determining the electron density profile from the data of microwaves refraction in a cylindrical plasma with a glass wall is considered theoretically in [29]. The case of discontinuous density (sharp plasma boundary) was studied too.

The angular scattering of a microwave flux in a fluctuating plasma was considered in [30]. Experimental studies were carried out on a pulsed reflex discharge, in which the strong density fluctuations appeared between the electrodes during the flow of current. The probing of the plasma was carried out with O-wave λ=8 mm in the cross-section of the cylinder at angles of 0…50°. The plasma was formed in a glass cylinder 100 mm in diameter. Refracting and scattered signals were received simultaneously using several antennas. Scattering was considered in the case of a medium with weak fluctuations, for which $\varepsilon = \overline{\varepsilon} + \delta\varepsilon$ and $\overline{\varepsilon} >> \delta\varepsilon$, where $\overline{\varepsilon}$ and $\delta\varepsilon$ are the average and fluctuating values of the dielectric constant. In this case, the intensity of scattering at a given angle was determined by only one component of spatial inhomogeneities. The value of the spatial inhomogeneity is found as a function of the plasma density from the scattering angles and the dependence *N(r)*.

The influence of a plane stratified statistical inhomogeneities of the medium on the electromagnetic wave refraction is considered in [31]. It was shown that the pulsations of the ray exit point are determined by the pulsations of the turning point in the medium. It happens when the gradients of the random component of the refractive index exceed the average gradient. The medium gradient produces regular refraction. The possibility of using the obtained results for diagnostics of statically inhomogeneous plasma is discussed.

The issues of reconstructing the fluctuation characteristics of an inhomogeneous plasma from the fluctuation characteristics of a refracted ray in the general cases of a plane stratified medium and cylindrically stratified medium were considered in [32]. It was assumed that the average density is a monotonically increasing function and the density fluctuations are sufficiently small. It is shown that for the case when a characteristic scale of fluctuation inhomogeneity is smaller than the characteristic scale of plasma inhomogeneity – density fluctuations in the vicinity of the ray turning point have a decisive effect on refraction.

2.2. DETERMINING THE ELECTRONIC TEMPERATURE PROFILE

Methods for determining the temperature profile of plasma electrons using refraction were theoretically considered in [20, 21]. In the case of a cylindrically stratified medium, the local value of the absorption coefficient is determined by measuring the total attenuation of the microwave ray at various angles of its incidence Ψ on the plasma layer from the equation [21]:

$$\mu_p(\Psi) = 4\frac{\omega}{c}\int_{r_0}^{R}\chi(r)\sqrt{1+r^2\left(\tfrac{d\theta}{dr}\right)^2}dr. \quad (10)$$

The dependence of the attenuation coefficient on the radius according to the known dependence χ(Ψ) [21]:

$$\chi(r) = \frac{1}{2\pi}\frac{\mathrm{d}}{\mathrm{d}r}\frac{r}{R}\sqrt{n^2(r)}\int_{\frac{r}{R}\sqrt{n^2(r)}}^{1}\frac{\mathrm{d}\mu_p}{\mathrm{d}\sin\Psi}\frac{\mathrm{d}\sin\Psi}{\sqrt{\sin^2\Psi - \frac{r^2}{R^2}n^2(r)}}. \quad (11)$$

The experimental determination of the density distribution and temperature of electrons along the radius using refraction was carried out in [33, 34]. The research was made in the decaying plasma of a pulsed reflex discharge. Plasma was probed by microwave at a wavelength λ_0=8.1 mm normally to the axis of plasma cylinder 100 mm in diameter. At first, the absorption coefficient $\mu_p(\Psi)$ and the angle of refraction $\theta(\Psi)$ of the microwave ray were measured for various angles of incidence Ψ, within 0…40° to determine $\mu_p(\Psi)$, and within 0…60° to determine $\theta(\Psi)$. Secondly, knowing the local values of the attenuation of microwave rays, as a result of collisions, the collision frequencies and electron temperature can be determined. A comparison of the temperature values obtained by this method with the probe method showed that they agree in order of magnitude.

2.3. DETERMINATION OF MAGNETIC FIELD DISTRIBUTION

The features of X-wave refraction in the cross-section of an anisotropic plasma cylinder are considered in [35]. Experimental studies were carried out on a pulsed reflex discharge. The plasma cylinder 100 mm in diameter was probed by microwaves (λ_0 = 8.1 and 14.3 mm) of various polarizations (O- and X-wave) in the range of magnetic fields from 0.15 to 1.4 T. The radial distribution of the magnetic field could be found in the case of dependence $\theta(\Psi)$ is known for waves of both polarizations. The *N(r)* and *H(r)* could be determined if the dependence of refraction angle on the incidence angle for X- and O-wave are known. A comparison between the *H(r)* curve obtained by the microwave method based on the microwave's refraction and the *H(r)* curve obtained by the probe method showed a difference of no more than 20%.

A method to measure the poloidal magnetic field distribution in the Tokamaks was proposed in [36]. The diagnostics method suggested consists of the following. Cylindrical plasma is probed by O-wave in the small cross-section of the torus at an angle to the equatorial plane of the torus. The frequency range order of electron plasma frequency is most suitable for measurements. The expression for the poloidal component of the magnetic field at a fixed angle of incidence and simultaneously at probing plasma by microwaves at several frequencies are obtained in this work. In addition, the case of probing at different angles of incidence with a constant probing frequency is considered. It is shown that by measuring the exit positions of the rays reflected inside the plasma versus frequency or the incidence angle one may find the poloidal field distribution in the tokamak.

3. EXPANDING THE FIELD OF APPLICATION OF MICROWAVE REFRACTION FOR DIAGNOSTICS OF PLASMA

The plasma diagnostics methods based on refraction are considered in section 2. In these methods, the inclination of horn antennas with respect to the plasma must be varied over a wide range. This condition may not always be technically feasible in experiments. This limits the use of these methods. On the other hand, the rays that leave the horn diverge and cross different layers of the plasma, which can in principle be used for plasma diagnostics. Therefore, to expand the capabilities of microwave diagnostics, it was proposed to use microwave rays coming out of a horn antenna obliquely to the plasma surface. The dependence of the deflection angle of the microwave ray, Θ, on the angle of its incidence, Ψ, onto the inhomogeneous plasma was calculated in [37-40]. The calculation data have shown that a part of microwave rays may enter the horn antenna installed at a fixed angle with respect to the plasma. The trajectory of microwave at 36 and 71 GHz for the case when maximum plasma density $N_{max} = 2\cdot10^{13}$ cm^{-3} is shown on the Fig. 2. In this case, the microwaves at 36 GHz hit the horn antenna shifted azimuthally at an angle of 60° with respect to the axis of the transmitting antenna unlike microwaves at 71 GHz.

In the experiments carried out in [38, 39] the scattering of microwaves at angles of ~ 60 and ~ 120° was recorded. Thus, the fundamental possibility of using microwaves refraction for multicomponent gas-metal plasma diagnostics and the possibility of using microwave methods based on the microwave's refraction were demonstrated in the studies [37-40].

Two methods based on refraction was proposed [41-47]. The first one is a method of plasma interferometry [41-45]. The second one is the method of determining local inhomogeneities of rotating plasma density via microwave refraction [46, 47].

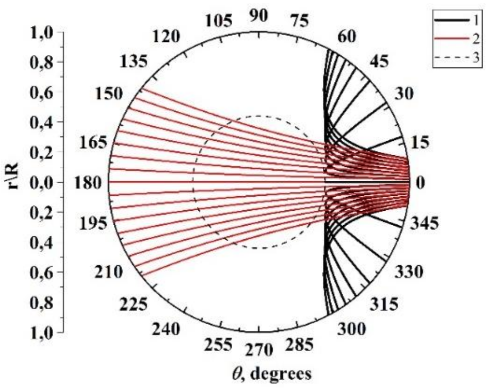


Fig. 2. Ray tracing of microwaves when maximum plasma density is $N_{max} = 2\cdot10^{13}$ cm^{-3}: 1 – frequency 36 GHz; 2 – frequency 71 GHz; radius of layers with critical density; 3 – $N_{cr.} = 1.6\cdot10^{13}$ cm^{-3}

3.1. INTERFEROMETRY AT THE OBLIQUE PROBING

Plasma interferometry at the oblique probing was considered in the works [41-45]. It was shown, that in the case of cylindrical symmetry when the additional phase due to reflection is taking into account, the phase of the electromagnetic wave transmitted through the plasma is defined as [44]:

$$\Phi_p(t) = \frac{2\omega}{c}\int_{r_0}^{R}\frac{n^2(r)rdr}{\sqrt{n^2(r)r^2 - R^2\sin^2\Psi}} - \frac{\pi}{2}. \qquad (12)$$

The calculations of the phase shifts [44, 45] at the probing through the plasma formation center and at the oblique probing showed that, in the latter case, the phase shift is observed both at $N_{cr} > N_{max}$ and at $N_{cr} < N_{max}$. In the case $N_{cr} < N_{max}$, the phase shift takes place to a certain N_{max} – value, when the microwave rays do not hit the receiving horn antenna. For the interferometry method [44, 45], based on the refraction of microwaves, two interferometers were used simultaneously. One interferometer, during normal probing, determined the plasma density across the plasma formation, and the second interferometer, with oblique probing at an angle 60º [41, 43, 44], at an angle 60 and 120º degrees [45], measured phase shifts of microwaves transmitted in the peripheral plasma layers. The plasma cylinder was probed by O-wave at a 37 GHz frequency. As a result of the experiment, the dependence of the product N_pL in time was determined, as well as the value of the average density of the peripheral plasma layers at interferometry with the use of refraction was estimated (Fig. 3).

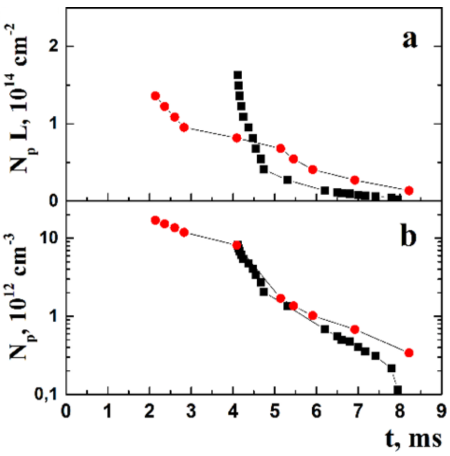


Fig. 3. Time dependence of the product N_pL (a), N_p (b): 1 – (■) $\varphi \approx 0^\circ$; 2 – (●) $\varphi_1 = 60^\circ$

3.2. DPETERMINING LOCAL INHOMOGENEITIES OF ROTATING PLASMA

The method for determining local inhomogeneities of the rotating plasma was checked and worked out on a rotating cylinder. The approbation was made on the rotating plasma of a pulsed reflex discharge [46, 47]. The one variant of the cylinder was made with three grooves which imitated plasma electron density oscillations with an azimuthal mode $m = 3$. It was found that the reflected signals (at normal and oblique incidence) from such type of cylinder are close in shape to the signals reflected from the rotating plasma surface (Fig. 4). It was shown that with using spectral and correlation analysis to the reflected signals, in the case of a cylinder with grooves, it is possible to find the number of grooves, as well as the angular frequency of rotation, the angle of azimuthal displacement between the grooves. Applying a similar technique for the case of a rotating plasma in [46], the angles of the azimuthal displacement of the grooves were determined as ≈ 120, 123, 118°; the angular frequency of rotation, which reaches the value $(2...4)\cdot10^4$ rad/s. The experiments have shown the fundamental possibility of using this method for diagnosing local inhomogeneities in plasma.

4. EFFECT OF REFRACTION ON THE ACCURACY OF MEASUREMENTS OF THE PLASMA PARAMETERS BY MICROWAVE METHODS

The microwave techniques described in Chapters 2 and 3 use microwave refraction for the plasma diagnostic. On the other hand, in the methods of interferometry, polarimetry, refraction is considered as a potential factor that can lead (in the case when the refraction is significant) to an inaccuracy in measuring plasma parameters. For example, the displacement of the ray from the rectilinear trajectory increases the length of the ray path, which leads to an error in the measurement of the phase during the plasma interferometry. For plasma polarimetry, errors arise due to a change in the angle between the wave vector and the vector of the external magnetic field. In addition, due to refraction, the microwave ray passing through the plasma may not reach the receiving horn, or in the case of multi-chord interferometry, it may hit the neighboring antenna, which will lead to an error in the density profile measurement.

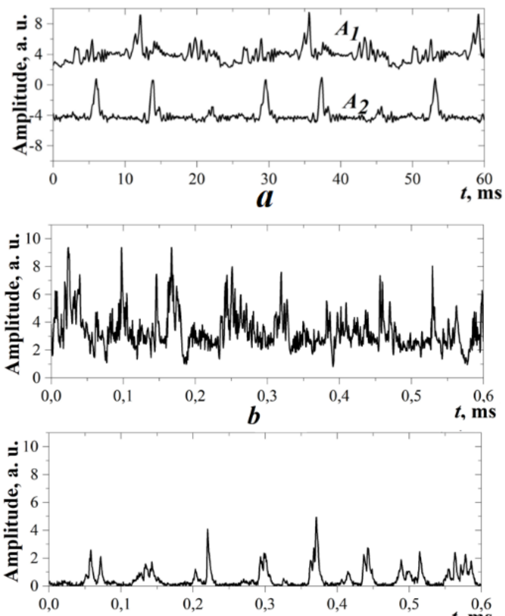


Fig. 4. Oscillograms of the reflected microwave signals at normal and oblique probing: a – for the cylinder with grooves (A_1, A_2 – normal and inclined probing respectively); b, c – reflected signals from the plasma at normal and inclined probing respectively

The influence of refraction on interferometric measurements of electron density was studied in [48-53]. In the geometrical optics approximation in the paper [50] the error of multichannel microwave plasma interferometry was considered. It was concluded that error arises due to refraction and because of the displacement of the ray at the aperture of the receiving antenna. In the case of a parabolic electron density distribution, the maximum error is about 4% of the maximum electron density. In [51] the effect of refraction on the accuracy of measurements the plasma density distribution with a multi-chord interferometer was considered. It was concluded that in order to reduce the effect of refraction the probe wavelength should be approximately 3 - 5 times shorter than the wavelength when measuring the average concentration along the diameter of the plasma formation. A method, based on an iterative algorithm, that compensates the effect of refraction on the probe wave was proposed in [52].

The effect of refraction on polarimetric measurements was analyzed in [49, 53-55]. The paper [55] describes the main physical factors limiting the accuracy of polarimetric measurements in Tokamak plasma, including refraction.

CONCLUSIONS

The generalization of both the author's and the literature data on the use of microwaves refraction in inhomogeneous plasma for its diagnostics is performed. The main microwave methods based on refraction for the inhomogeneous plasma diagnostics are presented. The ways of expanding the field of application of microwaves refraction for plasma diagnostics are shown. The effect of refraction on the accuracy of measurements of the plasma parameters by microwave methods is considered.

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ПРИМЕНЕНИЕ РЕФРАКЦИИ МИКРОВОЛН ДЛЯ ДИАГНОСТИКИ НЕОДНОРОДНОЙ ПЛАЗМЫ

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Приведен краткий обзор основных методов микроволновой диагностики неоднородной плазмы, использующих рефракцию микроволн. Эти методы позволяют определить распределения плотности плазмы и магнитного поля, частоту столкновений электронов и профиль электронной температуры. Кроме того, возможно определение средней плотности периферийных слоев плазмы и локальных неоднородностей вращающейся плазмы. Рассмотрено влияние рефракции на точность определения параметров плазмы при использовании микроволновых методов диагностики плазмы.

ЗАСТОСУВАННЯ РЕФРАКЦІЇ МІКРОХВИЛЬ ДЛЯ ДІАГНОСТИКИ НЕОДНОРІДНІЙ ПЛАЗМИ

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Наведено короткий огляд основних методів мікрохвильової діагностики неоднорідної плазми, що використовують рефракцію мікрохвиль. Ці методи дозволяють визначити розподіли густини плазми та магнітного поля, частоту зіткнень електронів і профіль електронної температури. Крім того, можливе визначення середньої густини периферійних шарів плазми та локальних неоднорідностей плазми, що обертається. Розглянуто вплив рефракції на точність визначення параметрів плазми при використанні мікрохвильових методів діагностики плазми.