COMPARATIVE ANALYSIS OF THE REFRACTION OF MICROWAVES AT DIFFERENT FREQUENCIES IN AN INHOMOGENEOUS PLASMA OF A HIGH POWER IMPULSE REFLEX DISCHARGE

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The trajectories of microwave rays at 36 and 71 GHz frequencies are calculated. A time dependences of an amplitude of scattered microwave signals at 36 and 71 GHz frequencies are experimentally measured. A comparison and analysis of experimental and calculated data, which are in satisfactory agreement, has been carried out.

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INTRODUCTION

Among the methods of plasma diagnostics, microwave methods occupy an important place [1-4]. The diagnostics methods that are based on the refraction of microwave rays in plasma [3-7] are also applied. By using the refraction, it is possible to determine a plasma density distribution. An essential requirement for application of this technique is using of narrow microwave rays supposing the fulfilment of the condition for geometric optics. These methods are feasible only with inclined microwave probing. To have a full set of data, the angle of transmitting horn antenna has to be varied with respect to the plasma [6, 7], what in practice is not always technically possible. For the case when there is no possibility to vary this angle, it was proposed [8, 9] to use the rays diverging from the transmitting horn antenna, which are directed at oblique angle to the plasma. In [10], calculations of the deviation angle φ of a microwave ray from an angle of its incidence ψ to no uniform plasma were made, which showed that part of a microwave rays could fall into a fixed horn antenna at a fixed angle with respect to the plasma. Experimentally, microwave ($f = 37$ GHz) scattering was registered at a fixed angle of ~ 60 ° and ~ 120° [10]. Experimental testing the method interferometry of plasma by inclined microwave rays, proposed in [8], was carried out in [11]. It has been experimentally shown the possibility of determining an average plasma electron concentration in the peripheral layers. Thus, the purpose of this study is comparative analysis of the refraction of microwave at different frequencies in an inhomogeneous plasma which should be useful to further developing the microwave methods based on refraction and help to increase its informatively and unambiguous measurements.

1. EXPERIMENTAL SETUP AND DIAGNOSTIC TECHNIQUES

Experiments on the microwave refraction in the plasma were carried out using the device "MAKET" [12]. In the device a high-power impulse reflex discharge in crossed $E\times B$ fields was realized. The stainless steel discharge chamber had the following dimensions: 20 cm in internal diameter, and 200 cm in length. A pulsed magnetic field of the mirror configuration (mirror ratio of 1.25, $B \leq 0.9$ T) and 18 ms in duration was created by a solenoid composed of six coils. The chamber was evacuated to a pressure of $1.33\cdot10^{-4}$ Pa and then filled with the igniter gas (Ar) at a pressure of 0.6 and 3 Pa. The plasma was produced by discharging a capacitor bank (capacity 560 μF, voltage ≤ 5 kV) between cold cathodes (diameter 10 cm) and the anode (the wall of the vacuum chamber). The multicomponent gas-metal plasma was produced in the mixture of the igniter gas and the sputtered cathode material. The cathodes were made of a composite material – Zr deposited on copper by the vacuum arc method.

The microwave measuring system is schematically represented in Fig. 1. Registration and measured of the scattered signal was carried out by a receiving horn antenna 5 shifted at the angle of 60 degrees with respect to the radiating antenna axis and detector (diode) 2.

Pyramidal horn antennas were used for transmission and receiving of a microwave radiation. A horn cross-section size (antenna aperture) was $a = b = 35$ mm, axial height is 92 mm. The horn antennas are mounted in diagnostic ports the design of which does not provide the variation of antenna tilt relatively to the plasma. Inclined probing was realized due to microwaves rays which directed to the plasma column obliquely. If the horn antenna aperture is taking into account, the angle of microwave radiation reception amounts to 60°± 9°. Simultaneously with the measured of the scattered signal, the microwave signal of the transmitted wave through the center of the plasma formation was measured by horn antenna 6 and detector 3. The mean plasma density across the plasma column was measured with using interferometer. Plasma was probed by microwave (O-wave) at frequencies 36 and 71 GHz.

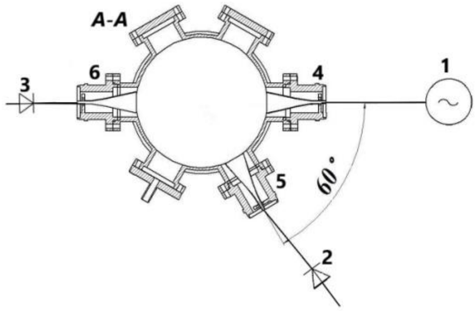

Fig. 1. Schematic representation of the measuring system. 1 – generator; 2, 3 – detectors for receiving microwave; 4 – the radiating horn antenna; 5, 6 – the receiving horn antennas

The space surrounding an antenna is usually subdivided into three regions [13]: reactive near-field, radiating near-field (Fresnel) and far-field (Fraunhofer) regions. These regions are determined depending on the distance from the antenna surface R: if $R < (2\cdot D^2 / \lambda)$ (where λ is the wavelength and D is the largest dimension of the antenna) it is near-field region and if $R > (2\cdot D^2 / \lambda)$ it is far-field region. The calculation showed that the far-field region is R > 31 cm and R > 65 cm for 36 and 71 GHz frequencies respectively. The diameter of cylindrical anode is less than this region. Thus plasma is located in the near-field region of antenna. Therefore, the calculations of the electric field and magnetic field components distribution at the aperture of the horn antenna for the wave at 36 and 71 GHz frequencies were made. The basic wave mode for the calculation was adopted as TE_{10}. All other modes are not essential for our waveguide. The calculations are performed by the method of moments. The results of calculation for waves at frequency 36 and 71 GHz are shown in the Fig. 2.

2. REFRACTION OF MICROWAVES IN AN INHOMOGENEOUS PLASMA CYLINDER

2.1. CALCULATION OF RAYS TRACING OF MICROWAVES AT TWO FREQUENCIES IN THE PLASMA CYLINDER

In the geometrical optics approximation, the differential equation for the trajectory of a microwave ray in a plasma cylinder looks like [5]:

$$\frac{d\varphi}{dr} = \frac{R\sin\Psi}{r^2\sqrt{n_{\mathrm{O}}^2(r) - \frac{R^2}{r^2}\sin^2\Psi}}, \qquad (1)$$

where Ψ is the angle between the line of propagation and the cylinder radius at the point of ray incidence on the plasma cylinder; φ is the deviation angle of the radius-vector from its initial position; R is the cylinder radius; r is the current coordinate; n_0 is the refraction index for the O-wave. The deviation angle φ of the microwave ray is dependent not only on the angle of the ray incidence ψ and the plasma electron density, but also on the plasma density profile.

In the case when the ratio of the effective collision frequency to the probing frequency is $\nu_{\mathrm{eff}} / \omega << 1$, the refraction index for the O-wave in the plasma is equal to [14]:

$$n_{\mathrm{O}}(r) = \left(1 - \frac{\omega_{\mathrm{p}}(r)^2}{\omega^2}\right)^{1/2} = \left(1 - \frac{N_{\mathrm{p}}(r)}{N_{\mathrm{cr.}}}\right)^{1/2}, \qquad (2)$$

where ω_{p} – frequency of plasma, ω – frequency of probing wave.

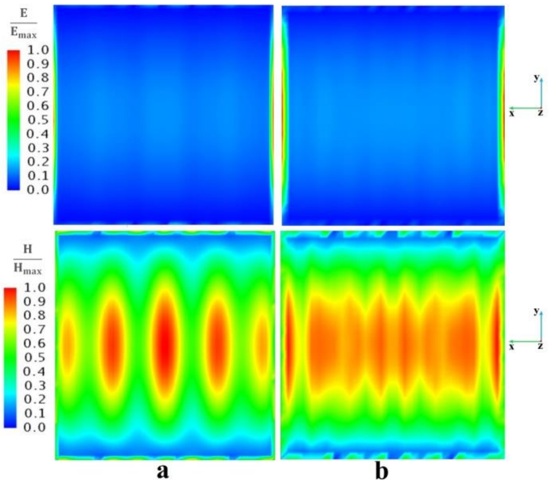

Fig. 2. Distribution of the electric and magnetic fields on the horn antenna aperture for wave at: a – 36 GHz; b – 71 GHz

Let's compare the influence of refraction on the propagation of microwave rays at frequencies 36 and 71 GHz. The critical densities $N_{\mathrm{cr.}}$ for these frequencies are $1.6\cdot10^{13}$ and $6.3\cdot10^{13}$ cm^{-3} respectively. The initial conditions are chosen according to the geometry and parameters of the experimental setup (see Fig. 1). The microwave ray's trajectory was calculated taking into account the aperture of the horn antennas and taking the density distribution in the form of $N_{\mathrm{p}}(r) = N_{\max}\cdot(1-(r/R)^2)$.

The calculation results obtained for the microwave rays trajectory in the plasma cylinder for three different cases are shown in Fig. 3. The axis of the radiating horn antenna is situated at angle of $\varphi = 0°$ (the angle of flare is 9°), the axis of the receiving antenna is situated at angle of $\varphi = 300°$ (the angle of flare is 9°).

In the first case, when the maximum plasma density is less than the critical $N_{\max} < N_{\mathrm{cr}}$ for both frequencies 36 and 71 GHz, the trajectory of microwave rays is shown in Fig. 3,a. Microwave rays due to refraction deviate from the rectilinear propagation and pass through the plasma. In the second case (see Fig. 3,b) the maximum plasma density is greater than the critical density $N_{\max} > N_{\mathrm{cr.}}$ for a frequency of 36 GHz. Wherein the microwave rays reflected from the plasma layer with a critical density can fall into the receiving antenna 5 (see Fig. 1). For a frequency of 71 GHz $N_{\max} < N_{\mathrm{cr}}$, the microwave rays pass through the plasma. In the third

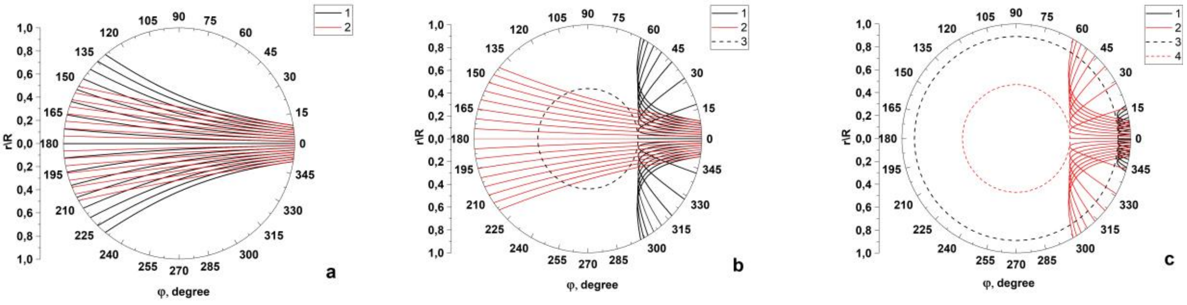

Fig. 3. Ray tracing of microwaves depending of different maximum values of density: a – $N_{\max} = 8\cdot10^{12}$ cm^{-3}; b – $N_{\max} = 2\cdot10^{13}$ cm^{-3}, c – $N_{\max} = 8\cdot10^{13}$ cm^{-3}. 1 – frequency 36 GHz; 2 – frequency 71 GHz; radius of layers with critical density; 3 – $N_{\mathrm{cr.}} = 1.6\cdot10^{13}$ cm^{-3}; 4 – $N_{\mathrm{cr.}} = 6.3\cdot10^{13}$ cm^{-3}

case, the maximum plasma density is greater than the critical $N_{\max} > N_{\mathrm{cr}}$ for both frequencies (see Fig. 3,c). Microwave rays at a frequency of 71 GHz, reflected from a plasma layer with a critical density, can hit the horn antenna 5 (see Fig. 1). For a frequency of 36 GHz calculations showed that when the radius of the plasma layer with N_{cr} is greater than ~ 5.2…6.3 cm, microwave rays do not enter the horn antenna 5 (see Fig. 1).

2.2. ATTENUATION OF MICROWAVE RAYS IN PLASMA

Absorption coefficient the general form [14]:

$$\mu_{\mathrm{p}} = 2\frac{\omega}{c}\int_0^{S_{\mathrm{p}}} \chi(s)ds\,, \tag{3}$$

where *χ(s)* absorption index in a given point *s* in the plasma, S_p the path of a microwave ray in a plasma. In the cylindrical layered medium equation 3 take form [5]:

$$\mu_{\mathrm{p}} = 4\frac{\omega}{c}\int_{r_0}^{R} \chi(r)\cdot\frac{r\cdot n(r)}{\sqrt{r^2\cdot n^2(r) - R^2\cdot\sin^2\psi}}dr\,, \tag{4}$$

where *χ(r)* absorption index in our case [14]:

$$\chi(r) = \frac{1}{2}\cdot\frac{\nu_{\mathrm{c}}}{\omega}\cdot\frac{\omega_{\mathrm{p}}^2}{\omega^2}\cdot\left(1-\frac{\omega_{\mathrm{p}}^2}{\omega^2}\right)^{-\frac{1}{2}}, \tag{5}$$

where v_c – effective collision frequency.

The time dependence of the maximum plasma density (see Fig 4,a) for the calculation was given by equation $N_{\mathrm{p}}(t)=0.51\cdot10^{21}\cdot(e^{-2016t} - e^{-9626t})$. This dependence is close to experimentally measured earlier in work [10]. The horn antenna aperture, wave frequency, distribution of plasma density and other parameters is the same as in paragraph 2.1. Absorption coefficient and absorption index were calculated by the formulas 4 and 5. The effective collision frequency was set equal to $v_{\mathrm{c}} = 0.001\cdot\omega$. (reflection from the opposite surface). At a density greater than the critical, the microwave signal does not pass through the plasma. With decreasing density, the attenuation of the signal decreases too, due to it its amplitude becomes higher. Curve on Fig. 4,b curve 2 shows that when plasma density reached value nearly $1\cdot10^{14}$ cm^{-3} the scattered signal at 71 GHz frequency has a maximum value.

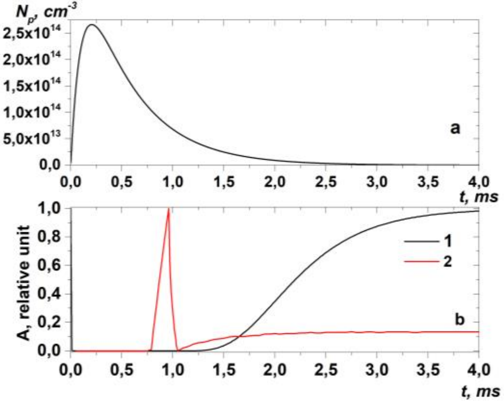

Fig. 4. Time dependences of: the plasma density (a); the amplitude of microwave signal at 71 GHz frequency transmitted through the center of plasma column (curve 1, b) and microwave scattered signal which hitting to horn antenna situated at angle 60 degrees with respect to the radiating antenna axis (curve 2, b)

3. EXPERIMENTAL RESULTS

The previous investigations of the plasma generated in a high-power pulsed discharge [12] have demonstrated that the time dynamics of the mean gas-metal plasma density can be divided by convention into three stages. The first stage presents the plasma creation and its density increase up to $N_{\mathrm{p}} = 1.7\cdot10^{13}$ cm^{-3}. The second stage is the plasma existence with the density attaining N_{p}~ 10^{14} cm^{-3} and more. The third stage presents the plasma density decrease and decay.

In the present experiments simultaneously with measurements of the scattered signal for wave at 36 GHz frequency (receiver antenna 5 (see Fig. 1)), through probing interferometry of plasma (Fig. 5) was made. And for wave at 71 GHz frequency transmitted signal through the plasma was registered (Fig. 6). According to the oscillogram of through probing interferometry which is shown on Fig. 5 (curve 1) the minimal amplitude of scatter signal for wave at 36 GHz was registered when plasma density achieved the critical density N_{cr}. This experimental result corresponds to the calculated result (see Fig. 3,c). According to the calculations it can be argued that the radius of the layer with critical density is more than ~ 5.2…6.3 cm.

From Fig. 6 (curve 2) it is seen that the rise of the scattered signal occurs approximately from 0.5 ms to 1.3 ms. At this time interval, the cutoff of the transmitted signal Fig. 6 (curve 2) is observed. Therefore, when plasma density is close or above the critical (N_{cr}) for wave at 71 GHz frequency, the maximum of the scattered signal is observed. This experimental result is opposite the result for wave at 36 GHz frequency. The calculated result (see Figs. 3,c and 4,b) is the same as experimental (see Fig. 6).

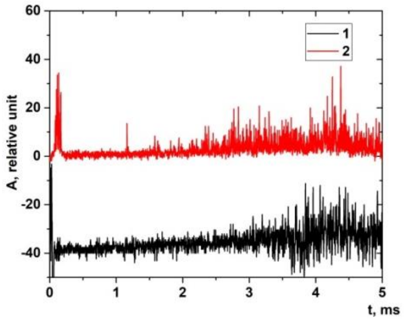

Fig. 5. Oscillogram of the thought probing interferometr (1) and microwave scatter at angles $\varphi_1 \approx 60^\circ \pm 9^\circ$ *(2). For both case the frequency of probing rays is 36 GHz*

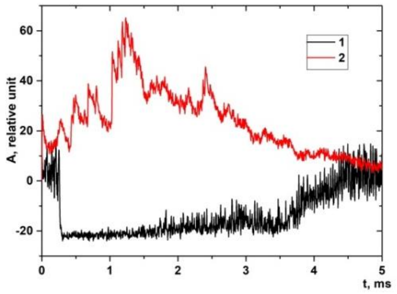

Fig. 6. Time dependence of the amplitude of the scattered signal at 71.45 GHz frequency at angle of 60° (1) and the oscillograms of the signal transmitted through the plasma (2)

CONCLUSIONS

The calculations of the ray trajectory at 36 and 71 GHz were performed. It is shown that, depending on the maximum density of the plasma, three cases of trajectory of microwaves with respect to the receiving antenna are possible. The time dependence of the amplitude of microwave scattered signal at 36 and 71 GHz frequencies were experimentally obtained. It was found that at frequency 36 GHz the minimal amplitude of receiving signal was registered when plasma density in the layer achieved the density N_{cr}. In contrast, for the same conditions, the maximum signal amplitude was observed when probing frequency was 71 GHz. The experimental and calculation method shows, that at a certain value of the plasma density, a wave with a lower frequency is reflected or absorbed in the plasma and becomes less informative. At the same time, a wave with a higher frequency can still hit on the receiving antenna. Therefore, the use of several frequencies can make methods of plasma diagnostics based on refraction more informative.

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СРАВНИТЕЛЬНЫЙ АНАЛИЗ РЕФРАКЦИИ МИКРОВОЛН НА РАЗЛИЧНЫХ ЧАСТОТАХ В НЕОДНОРОДНОЙ ПЛАЗМЕ МОЩНОГО ИМПУЛЬСНОГО ОТРАЖАТЕЛЬНОГО РАЗРЯДА

Ю.В. Ковтун, Е.В. Сюсько, Е.И. Скибенко

Проведены расчеты траектории микроволновых лучей на частотах 36 и 71 ГГц. Экспериментально измерены зависимости амплитуды рассеянных микроволновых сигналов на частотах 36 и 71 ГГц от времени. Проведено сравнение и анализ экспериментальных и расчетных данных, которые находятся в удовлетворительном согласии.

ПОРІВНЯЛЬНИЙ АНАЛІЗ РЕФРАКЦІЇ МІКРОХВИЛЬ НА РІЗНИХ ЧАСТОТАХ У НЕОДНОРІДНІЙ ПЛАЗМІ ПОТУЖНОГО ІМПУЛЬСНОГО ВІДБИВНОГО РОЗРЯДУ

Ю.В. Ковтун, Є.В. Сюсько, Є.І. Скибенко

Проведено розрахунки траєкторії мікрохвильових променів на частотах 36 і 71 ГГц. Експериментально виміряно залежності амплітуди розсіяних мікрохвильових сигналів на частотах 36 і 71 ГГц у часі. Проведено порівняння і аналіз експериментальних та розрахункових даних, що задовільно узгоджуються між собою.