REFRACTION OF MICROWAVES IN AN INHOMOGENEOUS ROTATING PLASMA

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The calculations of the angle of microwave ray deviation φ as a function of the angle of the ray incidence ψ on inhomogeneous plasma have shown that a part of the microwave rays may arrive at the horn antenna installed at a fixed angle relative to the plasma. The undertaken experiments have registered the microwave scattering at angles of ~ 60º and ~ 120º. The analysis of the experimental data has shown that at $N_p \geq N_{cr.}$ the observed scatter is connected with the microwave ray refraction in inhomogeneous plasma.

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INTRODUCTION

Experimental studies of plasma in crossed fields $E\times B$ are of interest for solving a wide range of purely physical and applied problems. One of these problems is the research into the multicomponent gas-metal rotating plasma, which is generated in the cross-field $E\times B$ devices, e.g., in the reflex discharge (Penning discharge) [1]. Among the methods of plasma diagnostics, the microwave techniques have gained wide recognition [2-4], including the methods based on microwave refraction in plasma [5-8]. The use of microwave refraction makes it possible to measure some plasma parameters in the plasma column cross-section at oblique incidence of the probing microwave ray. These measurements call for wide-range variations in the angle of horn antenna inclination relative to the plasma, and this is not always feasible in practice. On the other hand, the rays emitted from the horn diverge and intersect different plasma layers, and this can be used, in principle, for plasma diagnostics. This is of particular assistance in the case when the plasma density is above the critical value, and the end-to-end probing is impossible.

So, for extending the capabilities of the microwave diagnostics of the multicomponent gas-metal rotating plasma, it is reasonable to consider the possibility of using the electromagnetic wave refraction in the peripheral plasma column layers, this being of particular importance in the realization of magneto-plasma separation of substance into elements and mass groups [9-11].

1. EXPERIMENTAL INSTALLATION AND DIAGNOSTIC TECHNIQUES

Experiments on microwave refraction in inhomogeneous rotating plasma were performed at the "MAKET" facility [1], which can provide a high-power pulsed reflex discharge in crossed $E\times B$ fields. The multicomponent gas-metal plasma was generated in the environment of the ignition gas and the sputtered cathode material. The cathodes were made from a composite material, namely, copper, onto which *Zr* was deposited by the vacuum-arc method. More detailed description of the experimental facility can be found in ref. [1]. The experiments were carried out at the following initial conditions: the magnetic field of mirror configuration $B \leq 0.45$ T; the discharge voltage and current: $U \leq 4.2$ kV and $I \leq 1.8$ kA, respectively; *Ar* was used as an ignition gas at a pressure between 0.6 and 3 Pa.

The mean plasma density was determined by means of a microwave interferometer. Simultaneously with the interferometer measurements the scattered microwave signal was registered. The plasma cylinder was probed using an ordinary wave (O-wave) at the frequency f=37 GHz. In the experiments, pyramidal horn antennas were used for transfer and reception of the microwave radiation. The horn antennas were installed at diagnostic ports, the design of which does not allow variations in the angles of antenna inclination relative to the plasma. Therefore, precomputations were made to estimate the ray deflection angle versus the angle of ray incidence on the inhomogeneous plasma for a number of model plasma density distribution functions. The computation data have shown the possibility in principle to use in the given case the phenomenon of microwave refraction for plasma diagnostics. A more detailed discussion of the results will be given below.

2. MICROWAVE RAY TRAJECTORIES IN THE PLASMA CYLINDER

In the geometrical optics approximation, the differential equation of the microwave ray trajectory in the plasma cylinder (Fig. 1) has the form [8]:

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

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 running coordinate; n_O is the refraction index for the O-wave. The deflection angle of the ray radius-vector from its position on entering the plasma can be determined through integration of Eq. (1):

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

where r_0 is the turning point of ray trajectory, which is determined from the condition:

$$\frac{R^2}{r_0^2}\sin^2\Psi = n_O^2(r). \qquad (3)$$

In the case when the ratio of the effective collision frequency to the probing frequency is $\nu_{eff}/\omega << 1$, the refraction index for the O-wave in the plasma is equal to [3,4]:

$$n_O(r) = \left(1-\frac{\omega_p(r)^2}{\omega^2}\right)^{1/2} = \left(1-\frac{N_p(r)}{N_{cr.}}\right)^{1/2}, \qquad (4)$$

where ω is the probing frequency, $\omega_p(r)$ is the plasma frequency, $N_p(r)$ is the plasma electron density, $N_{cr.}$ is the critical plasma density.

In the experiments, we have used two receiving horn antennas, which were turned, relative to the radiating horn antenna by a fixed angle equal to $\varphi_1 = 60^{\circ}$ and $\varphi_2 = 120^{\circ}$. Taking into account the horn antenna aperture , the angle of microwave radiation reception amounts to $\varphi_1 \approx 60^{\circ} \pm 9^{\circ}$ and $\varphi_2 \approx 120^{\circ} \pm 9^{\circ}$, respectively.

In view of the above, calculations were made for the deflection angle φ of the microwave ray as a function of the angle ψ of the ray incidence on the inhomogeneous plasma. The calculation data are presented in Figs. 2 and 3. As it is obvious from Fig. 2, at certain $N_p(0)/N_{cr.}$ values a part of the rays may enter the receiving horn antennas. The calculations show (see Fig. 2) that with the parabolic plasma density profile at $0.25 < N_p(0)/N_{cr.} < 1$, the microwave ray comes to the second receiving horn antenna deflected relative to the radiating antenna by the angle $\varphi_2 \approx 120^{\circ} \pm 9^{\circ}$. At $1.75 > N_p(0)/N_{cr.} > 1$ the microwave ray comes to the first receiving antenna ($\varphi_1 \approx 60^{\circ} \pm 9^{\circ}$). Hence it follows that at the given initial conditions and density variations with time, e.g., density increase, the microwave signal is first registered by the second receiving antenna $\varphi_2 \approx 120^{\circ} \pm 9^{\circ}$ (there is no signal in the first antenna). Later on, at $N_p(0)/N_{cr.} > 1$ the signal is registered by the first receiving antenna $\varphi_1 \approx 60^{\circ} \pm 9^{\circ}$ (no signal in the second antenna), and in the case of $175 > N_p(0)/N_{cr}$ there is no signal in the both antennas. At plasma decay, a similar pattern is to be observed, but in the reverse sequence.

Naturally, the deflection 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 (see Eqs. (1)-(4)). Therefore, calculations were carried out for a number of model functions of plasma density distributions (see Fig. 3).

The curve behavior given in Fig. 3 is similar to that described above. In this case, at the same angle ψ of the microwave ray incidence the deflection angle φ of the ray is dependent on the plasma density profile. This dependence enables one to determine experimentally the plasma density profile [6, 7].

The obtained calculation data demonstrate the possibility in principle to use in the given case the phenomenon of microwave refraction for plasma diagnostics.

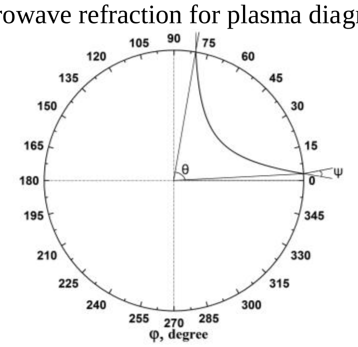

Fig. 1. Microwave ray trajectory in the plasma cylinder

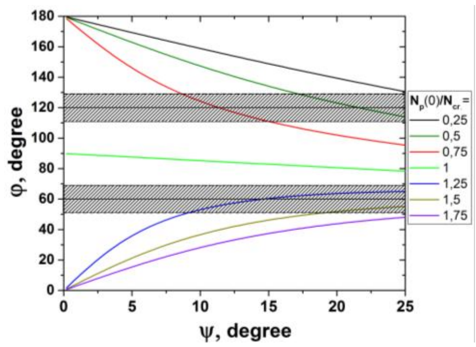

Fig. 2. Deflection angle φ of the ray versus the angle ψ of ray incidence on the inhomogeneous plasma for different $N_p(0)/N_{cr.}$ values (density profile is $N_p(r) = N_p(0)(1-(r/R)^2)$)

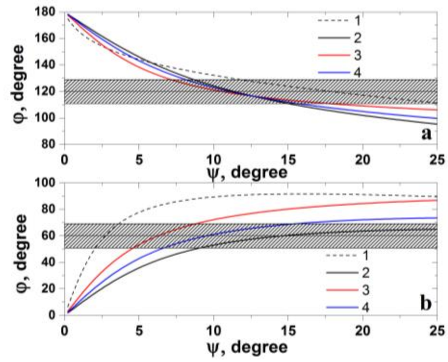

Fig. 3. Deflection angle φ of the ray versus the angle ψ of ray incidence on the inhomogeneous plasma. (a) $N_p(0)/N_{cr.} = 0.75$; (b) $N_p(0)/N_{cr.} = 1.25$. Density profile: 1 – $N_p(r) = N_p(0)(1-(r/R))$; 2 – $N_p(r) = N_p(0)(1-(r/R)^2)$; 3 – $N_p(r) = N_p(0)\cos(1-(r\pi/2R)^2$; 4 – $N_p(r) = N_p(0)J(2.405r/R)$

3. EXPERIMENTAL RESULTS AND DISCUSSION

The previous investigations of the plasma generated in a high-power pulsed discharge [1] 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 $N_p = 1.7 \cdot 10^{13}$ cm^{-3}. The second stage is the plasma existence with the density attaining $N_p \sim 10^{14}$ cm^{-3} and more. The third stage presents the plasma density decrease and decay.

In the present experiments, we have registered the microwave scatter at angles $\varphi_1 \approx 60^{\circ} \pm 9^{\circ}$ and $\varphi_2 \approx 120^{\circ} \pm 9^{\circ}$. Fig. 4 shows the scatter oscillogram taken at the angle $\varphi_1 \approx 60^{\circ} \pm 9^{\circ}$ and the time behavior of the mean plasma density. As is seen from Fig. 4,b, the scatter signal is registered at both the densities $N_p \geq N_{cr.}$ and $N_p < N_{cr}$. Note that at $N_p \geq N_{cr.}$, there is the span (0.7 to 1.2 ms), within which the scatter signal is absent. A similar situation is observed for scatter at the angle $\varphi_2 \approx 120^{\circ} \pm 9^{\circ}$ (Fig. 5). Fig. 6 shows the scatter dispersion oscillograms taken at the angles $\varphi_1 \approx 60^{\circ} \pm 9^{\circ}$ and $\varphi_2 \approx 120^{\circ} \pm 9^{\circ}$ with simultaneous registration of the signals. In the given case the following time sequence of events is observed (Fig. 6): (I) the signal is registered on the second antenna ($\varphi_2 \approx 120^{\circ} \pm 9^{\circ}$); (II) the signal is registered on the first antenna ($\varphi_1 \approx 60^{\circ} \pm 9^{\circ}$), there is no signal on the second antenna, the signal is not registered by both antennas; (III) the signal is registered on the first antenna ($\varphi_1 \approx 60^\circ \pm 9^\circ$), no signal on the second antenna, the signal is registered by both antennas. Actually, taking into account the time behavior of the plasma density, the observed pattern has appeared to be similar to that resulting from the analysis of the calculation data (see Sect. 2). This testifies that the approximations chosen for the calculations prove able to describe to some extent the experimental data. The presence in the two oscillograms of the region that shows no scatter signal is evidently indicative of the considerable size of the layer having the density $N_p \geq N_{cr.}$

The analysis of the calculation data (see Figs. 2 and 3) and the experimental data (see Figs. 4-6) shows that the occurrence of the signal scattered by the angle $\varphi_1 \approx 60^\circ \pm 9^\circ$ at the plasma density $N_p \geq N_{cr}$, and the signal scattered by $\varphi_2 \approx 120^\circ \pm 9^\circ$ at $N_p < N_{cr.}$ is connected with the microwave ray refraction in the inhomogeneous plasma. However, by the law of refraction, the presence of the scatter signal at $N_p / N_{cr.} < 0.25$ cannot be observed. In this case, the received scatter signals are due, on the one hand, to microwave scattering by plasma fluctuations [2-4, 12], and on the other hand, to possible reflection from the discharge chamber wall [13].

The estimations in the geometrical optics approximation show that at a low plasma density a single ray reflection from the chamber wall, followed by the ray entry into the receiving antennas, is possible. The radiation absorption in the metal chamber, whose dimensions are much greater than the wavelength (20 cm >> λ = 0.8 cm in this case), may be high regardless of the plasma absorbing capacity. The rays introduced through the antenna into the metal chamber experience multiple reflections from the chamber walls.

Moreover, the metal chamber can be also considered as a microwave resonator, where a great variety of oscillations can be excited [4, 14]. Accordingly, the plasma absorptivity of radiation brought to the chamber is determined by [4]:

$$A = \left(1 - |R|^2\right)\frac{A_{p1}}{A_{p1} + A_{w1}}, \qquad (5)$$

where R is the coefficient of wave reflection from the plasma resonator; A_{p1} is the wave absorption coefficient in single-passing through the plasma; A_{w1} is the absorption coefficient at reflection from the wall. With good antenna matching, the coefficient R can be low, $|R| << 1$. The power absorbed in reflection from the chamber walls is determined by effective conductance of the walls a, by the angle of incidence and polarization of the radiation. As the estimations of ref. [4] show, the coefficient A_{w1} ranges within 10^{-2} to 10^{-4} of the microwave. The calculations made in [4] have indicated that the maximum absorption coefficient is observed at $N_p \approx N_{cr.}$. The decrease in the absorption coefficient at lower concentrations is due to the increased passage of radiation through the plasma at high concentrations with rays reflection from the plasma. The present experiments (see Figs. 4, 5) have demonstrated the decrease in the scatter signal amplitude as the density decreases. This is evidently due to the increase in the collision frequency [15], and accordingly, in the absorption coefficient.

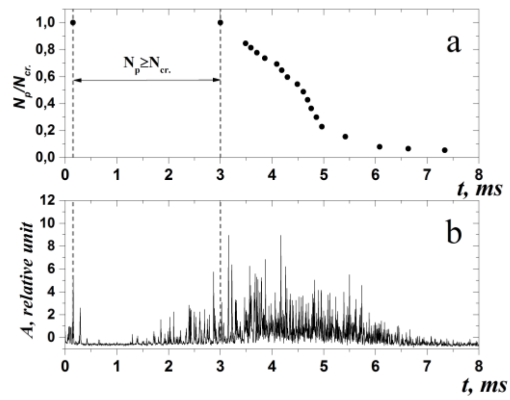

Fig. 4. Time dependence of the mean plasma density (a) and the signal scattered by the angle $\varphi_1 \approx 60^\circ \pm 9^\circ$ (b). ($U_{dis.}$ = 3.8 kV, U_B = 1.45 kV; p = 2.5 Pa)

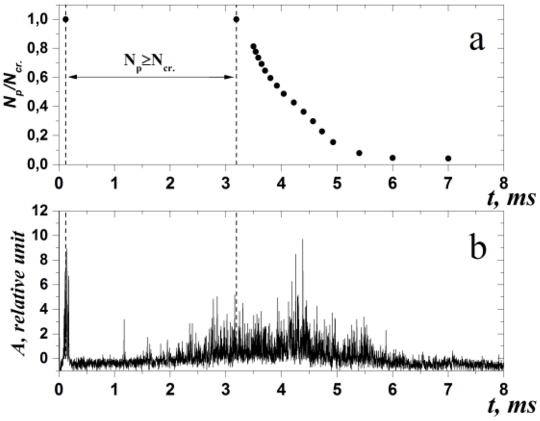

Fig. 5. Time dependence of the mean plasma density (a) and the signal scattered by the angle $\varphi_2 \approx 120^\circ \pm 9^\circ$ (b). ($U_{dis.}$ = 3.8 kV, U_B = 1.45 kV; p = 2.7 Pa)

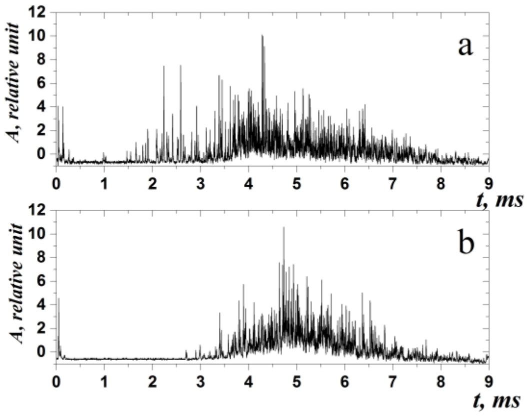

Fig. 6. Time dependence of the signals scattered by the angles $\varphi_1 \approx 60^\circ \pm 9^\circ$ (a) and $\varphi_2 \approx 120^\circ \pm 9^\circ$ (b). ($U_{dis.}$ = 3.7 kV, U_B = 1.4 kV; p = 1.16 Pa)

CONCLUSIONS

Calculations have been made to determine the dependence of the deflection angle of the microwave ray, φ, on the angle of its incidence, ψ, onto the inhomogeneous plasma. 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 present experiments have registered the microwave scatter at angles of ~ 60º and ~ 120º. The analysis of the experimental data has shown that at $N_p \geq N_{cr.}$ the observed scatter signal is related to the refraction of microwave rays in inhomogeneous plasma. At $N_p < N_{cr}$, the received scatter signal is due, on the one hand, to microwave scattering by plasma fluctuations, and, on the other hand, to possible reflection from the discharge chamber wall.

Thus, the present studies have demonstrated the possibility in principle of using the phenomenon of microwave refraction for diagnostics of multicomponent gas-metal rotating plasma.

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РЕФРАКЦИЯ МИКРОВОЛН В НЕОДНОРОДНОЙ ВРАЩАЮЩЕЙСЯ ПЛАЗМЕ

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Проведены расчёты зависимости угла отклонения φ микроволнового луча от угла его падения ψ на неоднородную плазму, которые показали, что часть микроволновых лучей может попадать в рупорную антенну, установленную под фиксированным углом по отношению к плазме. В проведенных экспериментах было зафиксировано рассеивание микроволн под углами ~ 60º и ~ 120º. Анализ экспериментальных данных показал, что при $N_p \geq N_{cr.}$ наблюдаемый рассеянный сигнал связан с рефракцией микроволновых лучей в неоднородной плазме.

РЕФРАКЦІЯ МІКРОХВИЛЬ В НЕОДНОРІДНІЙ ПЛАЗМІ, ЩО ОБЕРТАЄТЬСЯ

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

Проведені розрахунки залежності кута відхилення φ мікрохвильового променя від кута його падіння ψ на неоднорідну плазму показали, що частина мікрохвильових променів може потрапляти в рупорну антену, встановлену під фіксованим кутом по відношенню до плазми. У проведених експериментах було зафіксовано розсіювання мікрохвиль під кутами ~ 60º і ~ 120º. Аналіз експериментальних даних показав, що при $N_p \geq N_{cr.}$ спостережуваний розсіяний сигнал пов'язаний з рефракцією мікрохвильових променів в неоднорідній плазмі.