ABSTRACT

***Siusko Y. V.* Application of microwave refraction for diagnosis of inhomogeneous plasma.** Qualification scholarly paper: a manuscript.

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The methods of plasma diagnostics based on refraction have been developed in the dissertation work, namely: the measurement of microwave phase shift at inclined plasma probing with horn antennas fixed in space, the method of determination of azimuthal inhomogeneities of rotating plasma. Inclined probing (in the case of horn antennas fixed in space) has been proposed to implement using the peripheral part of the horn antenna radiation for the first time.

Measurement of the phase shift of waves in inclined probing and the method of determining the azimuthal inhomogeneities of rotating plasma can be used as the methods for diagnosing plasma, which make it possible to obtain information about peripheral plasma and determine azimuthal plasma inhomogeneities respectively. These methods can be used both in the study of laboratory plasma and in the devices of controlled thermonuclear fusion.

The work has calculated the trajectory of microwaves in the inhomogeneous plasma of the technological device MAKET. The results of the simulation indicate the possibility of using microwave refraction to study plasma with different density distributions using the peripheral part of the radiation of the horn antenna fixed in space in relation to the plasma.

In the study of the plasma of pulsed reflective discharge in the MAKET device, the phase shift of the waves has been measured with inclined probing, which made it possible to obtain information about the plasma parameters in the peripheral layers of plasma formation at time intervals when probing through the plasma formation center is impossible. Experimental verification and testing of the method for determining the

azimuthal inhomogeneities on a mechanical model that simulates the azimuthal inhomogeneities of a rotating plasma layer with a critical density have been carried out. Experimental testing of this method on the inhomogeneous plasma of a pulsed reflective discharge has shown its suitability and prospects for measuring the azimuthal inhomogeneities of the plasma.

The first section has described the main methods of plasma diagnostics: probe, corpuscular, laser, optical, microwave. Among microwave methods, the most common active methods have been identified and described: the method of interferometry, reflectometry. The basic principles and bases of the method of geometric optics have been given, the main criteria of possibility of its application for the description of distribution of microwaves in plasma have been given. Refraction as a concept of geometric optics has also been considered; the main methods of microwave plasma diagnostics using microwave refraction have been described. The influence of refraction on the accuracy of determination of plasma parameters when using microwave methods of plasma diagnostics has been shown.

The second section has described the MAKET installation, which implements a powerful pulsed reflective discharge in the crossed electric and magnetic fields. The main parameters of the installation and its main systems have been described: control systems, electric discharge and magnetic systems, vacuum system and working gas supply system. The design features of pulsed, high-voltage electric discharge and magnetic systems of electrophysical installation, which serves to obtain and study of multicomponent gas-metal plasma, have been considered and described. Electrical diagrams of electromagnetic and electric discharge systems have been given; their principle of operation has been described. The calculations of the dependence of voltage, charge and current in the *RLC* circuit of the magnetic system have been performed. The experimentally measured values of the amplitude and duration of the discharge current pulse through the magnetic system have been compared with the calculated ones, which has shown that the discrepancy between the duration of the current pulse and its amplitude does not exceed ± 2%. The possibilities of the vacuum system and the working gas supply system have been described.

The third section has described the geometric parameters of the horn antennas of the MAKET installation, and has evaluated their main radiating characteristics. The calculations of the effective surface area and the utilization factor of the horn antenna surface, the distribution of the Poynting vector have been performed. From the calculated and experimental data it is established that the distribution of the Poynting vector and the measured amplitude of the microwave signal by the detector are qualitatively similar and coincide in shape. Calculations and measurements have been performed along the x coordinate, to the right or left up to 150 mm, in parallel to the opening of the horn antenna; $x = 0$ mm – the coordinate of the antenna axis, calculation step is of 1 mm, $y = \text{const}$, $z = \text{const}$. The analysis of the calculated and experimental data has shown that the receiving characteristics of the antenna fully meet the conditions of its use at 37.2 and 71 GHz for the experiments with microwave refraction on the MAKET installation.

The calculations of the trajectories of microwave beams in inhomogeneous plasma have been carried out taking into account geometrical parameters of the MAKET installation, geometrical arrangement of horn antennas, their basic characteristics and plasma parameters. Trajectory calculations have been performed for different density profiles with a maximum on the axis of plasma formation, at different values of angles of incidence, maximum density and probing frequencies. The obtained calculated data of the trajectory of microwave beams for the parabolic density profile with a maximum on the axis of plasma formation demonstrate the fundamental possibility of using microwave refraction to diagnose plasma in the MAKET installation with horn antennas fixed in space. It has been shown that the use of microwave refraction at frequencies of 37.2 and 71 GHz makes it possible to expand the possibilities of microwave plasma diagnostics in the MAKET installation.

Taking into account the results obtained by modeling, the experiments have been performed using refraction in the MAKET installation. The experiments have shown that, depending on the plasma density, the microwave beams at a frequency of 37 GHz fall on the horn antennas placed at an angle of 60° and 120° in relation to the axis of the radiating antenna. As the density increases, the microwave signal is registered by the receiving antenna at first at an angle of $\varphi_2 \approx 120° \pm 9°$. Later, when $\frac{N_p(0)}{N_{cr}} > 1$ ($N_p(0)$ – plasma electron density on the plasma forming axis, N_{cr} – critical density) the signal is registered by the receiving antenna at an angle of $\varphi_1 \approx 60° \pm 9°$ (there is no signal in the antenna at an angle of $\varphi_2 \approx 120° \pm 9°$), and in the case of $1{,}75 > \frac{N_p(0)}{N_{cr}}$ there is no signal for both antennas. When the plasma decays, a similar pattern is observed, but in reverse order. It is shown that the same pattern is observed in the calculations. The experiments on the study of microwave refraction at frequencies of 36 and 71 GHz have demonstrated the possibility of receiving microwaves on a horn antenna shifted by an angle of 60° in relation to the axis of the radiating antenna. Both calculations and experiments show that in the case when $N_p > N_{cr}$, for a wave at 36 GHz, the signal on the antenna is absent, and for a probing frequency of 71 GHz for the same conditions, the signal was registered, on the contrary, at its maximum level. Therefore due to the inclined probing of plasma by microwaves at different frequencies, probing of different layers of plasma can be carried out. Conducted studies have shown the possibility of using the peripheral part of the radiation of the horn antenna for the diagnosis of plasma in cases where the angle of the horn antennas cannot be changed.

In the fourth section, it has been proposed: to probe the peripheral layers of the plasma by inclined microwaves, to measure the phase shift the waves that passed through the peripheral layers of the plasma by using the peripheral part of the horn antenna radiation. To do this, we have calculated the phase of microwave beams in the inhomogeneous plasma with through probing (through the axis of the plasma cylinder) and with inclined probing, which is realized due to the microwave beams falling obliquely on the surface of the plasma being probed. The initial conditions of the task have been taken according to the geometry of the MAKET installation, the position and parameters of the horn antennas, the typical parameters of the plasma generated in the installation. The results of the calculations have shown the fundamental possibility of using the measurement of the phase shift of the microwave with inclined probing for the diagnosis of peripheral plasma layers. In the case of measuring the phase shift of waves with inclined probing when receiving microwaves at angles of 60° ± 9° and 120° ± 9°, phase shift is observed both at $N_{cr} > N_{max}$ and at $N_{cr} < N_{max}$ ($N_{\max}$ – the maximum plasma density). This suggests that, using microwave phase shift measurements with inclined probing with the horn antennas fixed in space, it is possible to record phase shifts even if the plasma density is above the critical value and through interferometry is not possible. Also, the radius of the critical plasma layer r_{cr} with a density equal to N_{cr} has been calculated, when due to refraction and reflection from the critical density layer part or all of the microwave beams enter the receiving antenna at an angle of 60°. At the parabolic density profile, r_{cr} belongs to the range between 5.2 and 6.3 cm. Calculations of r_{cr} show that for other density distribution functions along the radius, the values of r_{cr} are in the range of 4.5 and 6.5 cm. The experiments on determination of plasma density by means of interferometry at through probing and probing using microwave refraction when receiving horn antennas are located at angles of 60° and 120° have been described. These experiments have shown that the use of microwave refraction allows to measure the density of plasma in its individual layers when it is impossible to probe the plasma formation through. Thus, for $N_{\mathrm{cr}} < N_p$ (N_p is the plasma electron density), the phase shift is absent during the probing through the center of plasma formation and the phase shift is present during the inclined probing. The average time of absence of phase shifts during the probing through the center of plasma formation has been experimentally measured as $\tau_1 = 3.12 \pm 0.21$ ms and during the inclined probing it has been measured as $\tau_2 = 1.04 \pm 0.25$ ms. The dependence of the multiplication $\overline{N_p L}$ (the multiplication of the average plasma density on the optical path L of microwaves in plasma) on time has been determined, and the value of the average plasma density during the probing through the plasma center and the inclined probing has been estimated. In both cases of probing (at a plasma density of $N_{cr} > N_{\mathrm{p}}$) a close value of the average plasma density has been obtained, which adequately conforms with the assumption of reflection of microwave beams from the opposite surface of the chamber.

Conducted studies have shown the ability to use the microwave phase shift measurements at inclined probing to diagnose peripheral plasma.

In the fifth section, the method for determining the azimuth inhomogeneities of rotating plasma has been proposed. The method is based on the spectral and correlation analysis of plasma-reflected signals at inclined and normal incidence on the plasma surface. Verification and testing of the method for determining the azimuthal inhomogeneities of the rotating plasma density has been performed on a mechanical model. Experimental testing of the method has been carried out on the MAKET installation, which implements a pulsed reflective discharge in crossed $E \times B$ fields. Plasma was probed by the O-wave at a probing frequency of f = 36 GHz. The nature of the signals reflected from the plasma is similar to that obtained earlier for the mechanical model of the cylinder with three grooves. The analysis of the signals reflected from the plasma has allowed: to detect the fluctuations of plasma electron density with azimuthal mode m = 3; to determine the values of the angles of azimuthal displacement of the grooves as ≈ 120°, 123°, 118°; to measure the angular velocity of rotation of azimuthal inhomogeneities in the range from $2 \cdot 10^4$ to $4 \cdot 10^4$ rad/s. The performed experimental verification, testing and approbation of the method of determination of azimuthal inhomogeneities of rotating plasma have shown the prospects of the method of plasma diagnostics studied in the dissertation.

Key words: microwaves, beam, refraction, plasma, density, discharge, pulse, interferometry, microwave methods, generator, antenna, spectrum, magnetic field, horn.