INVESTIGATION ON THE POSSIBILITY OF DETERMINING PLASMA PARAMETERS BY THE METHOD OF LOW-FREQUENCY DIAGNOSTICS

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A possibility of determining some parameters (density, collision rate, magnetic field strength, mass-and-ion charge) of the plasma being in a magnetic field is under consideration. Peculiarities in the change of probing wave refraction and absorption values depending on the plasma parameters are investigated. Appreciation is made of the possibility for plasma diagnostics by means of probing using low-frequency electromagnetic waves with frequencies of ion-cyclotron range.

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INTRODUCTION

The use of high-frequency electromagnetic waves for plasma diagnostics is possible only with fulfillment of the following conditions: the probing frequency ω significantly exceeds the ion-cyclotron frequency ω_{ci} and the electron-collision rate ν_{ei} , the electron velocity is significantly lower than the phase wave velocity and the plasma parameters are changing slightly on the wave length. In this case the ion influence on the wave propagation can be neglected. The development of investigations on plasma physics, on plasma-technology directions and the urgency of solving the problem of controlled thermonuclear fusion have leaded to the building of large-scale facilities with longitudinal and transverse dimensions of several meters and more. Thus the diagnostic measurements of plasma parameters with low-frequency (LF) waves become possible [11]. The plasma wave propagation in this range has been investigated thoroughly [2,3] in connection with the problem of creating high frequencies (HF) and heating fusion plasma [4-8]. Also, in the monograph [9] the plasma propagation in the isotropic and magnetoactive plasma waveguides has been investigated.

Moreover, similar global problems arise and are solved in the allied fields of science and technique. For example, in the ecology [10] it is important to know an elemental composition of samples from various soils to determine their destination and different conditions of their maintenance. Currently for this purpose one uses laser technologies and methods. However, other techniques are to be applied to solve the problems of soil controlling and decontamination from pollution with different metals including heavy metals and their compounds. Therefore, taking into account [1-9] and other physical and engineering developments [10], the study of low-frequency waves to be used in the plasma diagnostics (LFD) seems possible and expedient. New opportunities of low-frequency plasma diagnostics can be of interest also for the investigation of multicomponent plasma parameters in a magnetic field, in particular, in the presence of ions with large-masses and high charge values.

1. POSSIBILITY OF DETERMINING PLASMA PARAMETERS

The distribution of low-frequency electromagnetic waves (having the frequencies of ion-cyclotron waves) moving in the plasma along the magnetic field is described, with taking into account the ion motion [1,2], by the following equations:

$$(\mu - i\chi)^2 = 1 - \left[\omega_p^2 / (\omega^2 - i\nu\omega + \omega\omega_{ce} - \omega_{ci}\omega_{ce})\right], \quad (1)$$

$$A = (\mu^2 - \chi^2) = 1 - \frac{\omega_p^2(\omega^2 \pm \omega\omega_{ce} - \omega_{ci}\omega_{ce})}{(\omega^2 \pm \omega\omega_{ce} - \omega_{ci}\omega_{ce})^2 + \nu^2\omega^2}, \quad (2)$$

$$B = 2\mu\chi = \frac{\omega_p^2 \nu\omega}{(\omega^2 + \omega\omega_{ce} - \omega_{ci}\omega_{ce})^2 + \nu^2\omega^2}, \quad (3)$$

$$\mu^2 = \frac{A + \sqrt{A^2 + B^2}}{2}, \quad (4)$$

$$\chi^2 = \frac{B^2}{2}\left(A + \sqrt{A^2 + B^2}\right), \quad (5)$$

where μ is the refraction coefficient, χ is the absorption coefficient , ω_p is the plasma frequency, ω_{ce} and ω_{ci} are the electron and cyclotron frequencies, A and B are the components of a medium complex dielectric permittivity. A similar set of equations can be written for the case of the plasma with Maxwell distribution [2] when the initial plasma state is equilibrium, i.e. is determined by the velocity Maxwell particle distribution.

Taking into account that $\omega_p^2 = 4\pi N_e^2 / m_e$, $\omega_{ce} = eH / m_e c$, $\omega_{ci} = zeH / m_i c$, $m_i = am_p$, the values μ and χ are determined by the plasma density, magnetic field intensity, collision rate, ion mass and its charge. Therefore, let us consider the possibility of determining the above mentioned parameters due to the investigation of peculiarities in the variation of refraction and absorption coefficients depending on these parameters. Thus, the possibilities of the diagnostics with the use of low-frequency electromagnetic wave probing will be estimated.

Fig. 1 represents the frequency dependences of the refraction coefficient μ and absorption coefficient χ for different plasma density values (from $1{\cdot}10^{12}$ to $1{\cdot}10^{13}$ cm^{-3})

with the magnetic field intensity H = 2 kOe, collision rate $\nu \simeq 10^9$ s^{-1} and ion mass $a = m_i/m = 1$. The dependences are of a resonance character. The resonance values of frequencies for μ and χ and, consequently, the resonance width are dependent on the plasma parameters. Also note, that the refraction coefficient μ is determined by phase measurements and the absorption coefficient χ is determined by amplitude measurements. As the amplitude measurements are simpler in the experimental realization and subsequent processing. in the following consideration we will operate only with the absorption coefficient χ. The resonant frequency changes with the magnetic field, ion mass and its charge changing. At the same time, the plasma density and collision rate variation do not lead to the resonant frequency change and influence only on the amplitude and the width of the resonance curve. So, the parameters H, a, z can be determined by measuring the resonant frequency; the density is determined by measuring the amplitude of absorption coefficient χ; the collision rate – by measuring the resonance curve width at its half-width maximum amplitude. In addition, it should be taken into account that the possibility of these measurements depends on the wave attenuation and wave length in the plasma. Analysis of the refraction and absorption coefficients as a function of the frequency at different density values in the range of $N = 10^{12}…10^{13}$ cm^{-3} shows that the resonant region in the curves (see Fig. 1) narrows with collision rate decreasing, and the resonant frequency does not depends on the plasma density and frequency rate.

An important aspect for realization of the plasma diagnostics technique offered is the fact that during resonance the wave undergoes a strong attenuation. The attenuation estimations give the following results. For example, if $\nu = 10^9$ s^{-1} the attenuation coefficient in the chosen density range reaches the values of F = 0.67…0.21 Np/cm or the amplitude decrease per cm A_0/A = 1.96…1.21; for $\nu = 10^7$ s^{-1} F = 6.7…2.1 Np/cm. Therefore it is more convenient to measure the attenuation at the frequency below the resonant one. So, when the frequency decreases, starting from the resonant region, by 340 HGz at $\nu = 10^9$ s^{-1} and by 30 kHz at $\nu = 10^7$ s^{-1} the wave attenuation in the plasma density range from 10^{12} to 10^{13} cm^{-3} is equal to 0.179…0.565 Np/cm and 0.077…0.24 Np/cm redpectively.

2. DESCRIPTION OF TECHNIQUES FOR LOW-FREQUENCY PLASMA DIAGNOSTICS

As is shown above, the dependences of characteristic parameters μ and χ of the low-frequency wave, in the region of ion-cyclotron frequencies, passing through the plasma are of a resonance character. To determine the multicomponent plasma parameters N, H, a, z, ν it is reasonable to use the dependences of wave parameters (μ, χ) on the resonant frequency. Consequently, it is necessary to know the values of the resonant frequency, resonance width at its half-amplitude. In this case the plasma probing is carried out by the frequency-modulated waves.

The density is determined by measuring the χ amplitude from the relation $\chi = f(\omega)$ (see Fig. 1) in the resonance point (region). The density is calculated from the quadratic equation such as $N = a_1\chi^2 + b_1\chi + c_1$, where the coefficients a_1, b_1, c_1 are determined from the calculated relations $\chi = f(\omega)$ for different plasma density values given in Fig. 1. For example, in the range of densities $N = 10^{11}…10^{12}$ cm^{-3} at the collision rate $\nu \approx 10^6$ s^{-1} the plasma density is determined via the absorption coefficient using the equation $N = 1.9 \cdot 10^4 \cdot \chi^2$. Thus, for the range of $N = 10^{11}…10^{12}$ cm^{-3} and the value $\nu \approx 10^7$ s^{-1} we obtain the following relation $N = 2.06 \cdot 10^6 \cdot \chi^2$.

The collision rate in the plasma is determined by the width of the resonance curves of the dependence $\chi = f(\omega)$ using the formula $\nu = a_2 \Delta\omega + b_2$ where the coefficients a_2 and b_2 are determined from the calculated dependences (Fig. 2). For example, when a=1, $\nu = (2.68 \cdot 10^2\, \Delta\omega + 4.46 \cdot 10^{-6})$ s^{-1}.

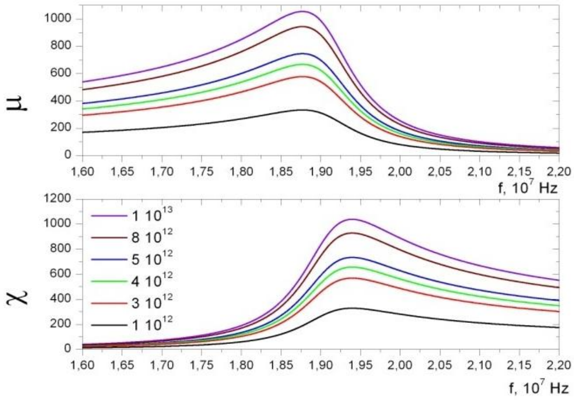

Fig. 1. Frequency dependences of the refraction coefficient μ and absorption coefficient χ at different density values (H = 2000 Oe, $\nu = 10^9$ s^{-1}, a=1, Z=1)

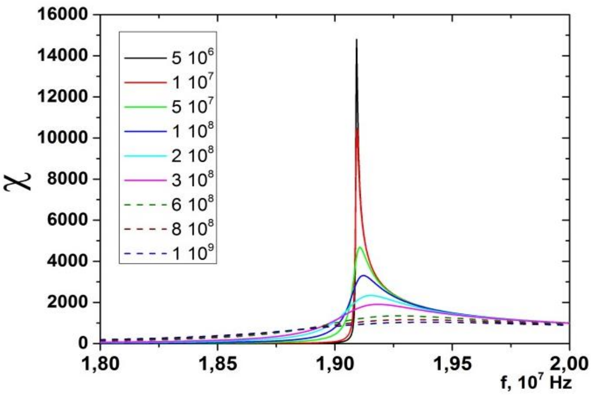

Fig. 2. Frequency dependences of the absorption coefficient χ on the collision rates. ($N = 10^{13}$ cm^{-3}, $\nu = 10^9$ s^{-1}, a=1, H=2000 Oe, Z=1)

The magnetic field intensity H in the plasma column region (or the change of H in this region under the plasma gas-kinetic pressure NkT) can be determined by the resonance frequency value using the dependence $\chi = f(\omega)$ given in Fig. 3 and the equation $H = (1.04 \cdot 10^4 \omega_{res} - 18.6)$ Oe. The dependence $H = f(N, \nu)$ is rather weak. The technique offered for determining the magnetic field intensity (or its changing) in the plasma column region can be of a great practical importance for the plasma with a sufficient high value $\beta = \frac{8\pi nkT}{H^2}$.

Knowledge of the multicomponent plasma ion mass a is of great importance for determining plasma composition and for solving some applied problems, in particular, upon the substance separation into elements and mass groups with application of magnetoplasma techniques. In this study we have found that the relative multicomponent plasma ion mass *a* is determined by the resonance frequency and width $\Delta\omega_{res.}$ the resonance curve at its half-width maximum amplitude, which can be determined from the dependences $\chi = f(\omega)$ (see Fig. 1). At H=2000 Oe, N= 10^{13} cm^{-3}, $\nu=10^9$ s^{-1}, z=1, $a=2{,}54\cdot10^4\ \Delta\omega+64$. Fig. 4 presents the frequency dependences of the relation $\chi = f(\omega)$ at different values of the relative ion mass in the range of a=12–56 with H=2000 Oe, N= 10^{13} cm^{-3}, $\nu=10^9$ s^{-1}.

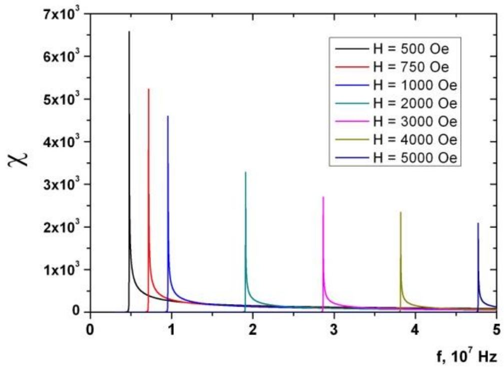

Fig. 3. Frequency dependences of the absorption coefficient χ at different values of the magnetic field ($N=10^{12}$ cm^{-3}, $\nu=10^7$ s^{-1}, a=1)

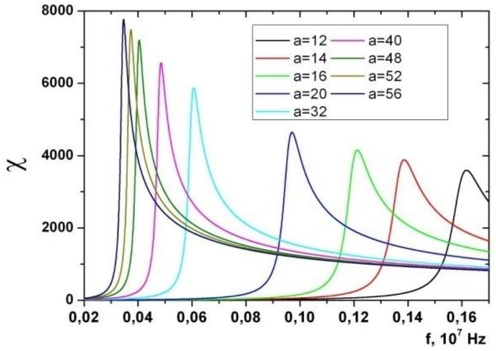

Fig. 4. Frequency dependences of the absorption coefficient χ at different values a ($N = 10^{13}$ cm^{-3}, $\nu=10^9$ s^{-1}, H=2000 Oe, Z=1)

The charge *z* of the multicomponent plasma ions is determined also from the dependence $\chi = f(\omega)$ (Fig. 5). The plasma parameters *N* and *ν* do not exert significant influence on the behavior of this dependence and on the value *z*.

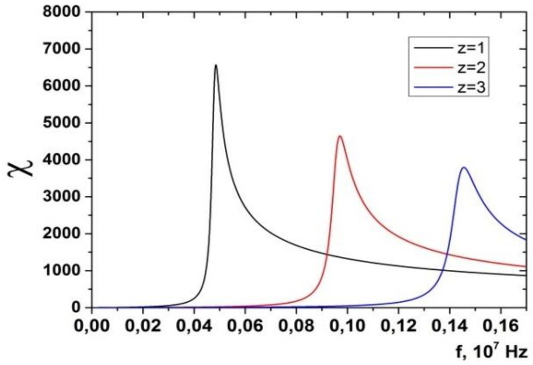

Fig. 5. Frequency dependences of the absorption coefficient χ at z=1, 2, 3 ($N=10^{13}$ cm^{-3}, $\nu=10^9$ s^{-1}, a=40)

Since for determining some of the multicomponent plasma parameters, such as collision rate, ion mass, it is necessary to know the width ω_{res} of the resonance curve at its maximum half-width amplitude, in our study we have determined the dependences of the resonance curve width $\chi = f(\omega)$ on the collision rate (Fig. 6).

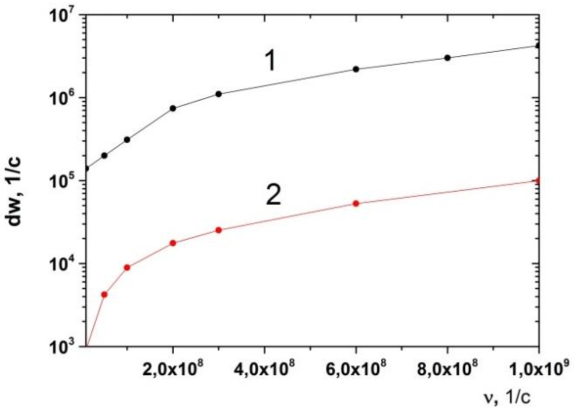

Fig. 6. Frequency dependences of the resonance curve width of the absorption coefficient χ on the collision rate, 1 – a =1; 2 – a =40 ($N=10^{13}$cm^{-3}, H=2000 Oe, Z=1)

CONCLUSIONS

A possibility of determining the multicomponent plasma parameters in a magnetic field by the method of low-frequency electromagnetic wave probing is analyzed. It is established that the frequency dependences of the refraction and absorption coefficients of the electromagnetic waves are of a resonance character. Using the LF waves for multicomponent plasma probing along the magnetic field it is possible to determine the plasma ion component density, collision rate, local magnetic field intensity or its change, find the presence of ions having different mass and charge. For this the probing wave frequency should be modulated and the main corresponding resonance characteristics (for example, absorption coefficient), in particular, the resonance frequency and resonance curve width at its half-width maximum amplitude, should be measured.

Computer simulation was applied to obtain the resonance dynamics by changing the above-mentioned plasma parameters (shown in the plots of Figs. 1-5. The curves of Figs. 1-5 were used to derive the simplified analytical expressions for calculation of plasma parameters with taken initial conditions.

So, the use of LF waves for the magnetoactive plasma probing enlarges the arsenal of equipment and techniques for plasma diagnostics with electromagnetic waves.

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ИССЛЕДОВАНИЕ ВОЗМОЖНОСТИ ОПРЕДЕЛЕНИЯ ПАРАМЕТРОВ ПЛАЗМЫ С ПОМОЩЬЮ МЕТОДОВ НИЗКОЧАСТОТНОЙ ДИАГНОСТИКИ

Ю.В. Ковтун, И.Б. Пинос, А.И. Скибенко, Е.И. Скибенко

Рассмотрена возможность определения некоторых параметров плазмы (плотности, частоты соударений, напряженности магнитного поля, массы и заряда ионов), находящейся в магнитном поле, за счет исследования особенностей изменения показателей преломления и поглощения зондирующей волны от этих параметров. Оценена возможность диагностики плазмы с помощью зондирования низкочастотными электромагнитными волнами с частотами порядка ионно-циклотронных.

ДОСЛІДЖЕННЯ МОЖЛИВОСТІ ВИЗНАЧЕННЯ ПАРАМЕТРІВ ПЛАЗМИ ЗА ДОПОМОГОЮ МЕТОДІВ НИЗЬКОЧАСТОТНОЇ ДІАГНОСТИКИ

Ю.В. Ковтун, І.Б. Пінос, А.І. Скибенко, Є.І. Скібенко

Розглянута можливість визначення деяких параметрів плазми (густини, частоти зіткнень, напруженості магнітного поля, маси і заряду іонів), що знаходиться в магнітному полі, за рахунок дослідження особливостей зміни показників заломлення і поглинання зондуючої хвилі від цих параметрів. Оцінена можливість діагностики плазми за допомогою зондування низькочастотними електромагнітними хвилями з частотами порядку іонно-циклотроних.