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UHF REFLECTOMETRY OF PLASMA BY EXTRAORDINARY WAVES WITH A FREQUENCY BELOW THE ELECTRON CYCLOTRON FREQUENCY

Comparative dependences of the refractive index on the profiles of a plasma density and a magnetic field are found for ordinary and extraordinary waves under various conditions of plasma probing. Advantages of using the extraordinary wave (X-wave) with a frequency below the electron cyclotron frequency for the diagnostics of a magnetoactive plasma are analyzed with regard for the experimental conditions on a U-3M torsatron. The refraction of microwaves at the oblique plasma probing is studied taking the poloidal component of a magnetic field into consideration. The Doppler shift of an X-wave reflected from the moving plasma layer is found to exceed that of an ordinary wave (O-wave).

Keywords: UHF reflectometry of plasma, Doppler shift.

1. Introduction

In recent years, the circle of problems in plasma researches that can be or were solved with the use of UHF reflectometry [1] is extended. This circumstance predetermines the fact that the number of types of UHF signals applied to the plasma probing increases. In particular, the two-frequency and two-polarization probings, broadband probing, and reflectometry with the help of ultrashort and noise UHF signals could be mentioned [2, 3].

In works [1–13], the results were reported concerning the application of UHF methods to the magnetoactive plasma diagnostics, in which probing was carried out with the use of O- and X-waves, and the corresponding advantages were analyzed. Frequencies higher than the electron cyclotron frequency are used more often, which enables the sensitivity of the method to be enhanced in the cases where the density is much less than the critical one. In this work, we use the waves with frequencies $f_0 < f_{ce}$, where f_0 and f_{ce} are the probing and electron cyclotron frequencies, respectively, and analyze the possible advantages of this probing, which follow from the features in the dependences of the refractive index for the wave concerned on the spatial and temporal distributions of the plasma density and the magnetic field. The corresponding calculations were carried out, by using the parameters of a Uragan-3M torsatron [9]. The capabilities of this probing can be useful for the determination of plasma density profiles, the velocity characteristics in plasma layers with the use of Doppler reflectometry, the correlation length of plasma fluctuations by means of correlation reflectometry, and so forth. The study of those characteristics is important, when the conditions for the formation of internal and boundary transport barriers responsible for the transition into the regime of improved plasma holding in a magnetic trap are determined, as well as when the conditions for the plasma self-cleaning from impurities and the optimum conditions for plasma technologies are created.

2. Features in the Propagation and Reflection of an Extraordinary Wave with $f_{ce} > f_0$

The features in the propagation and the reflection of extraordinary waves in a magnetoactive plasma

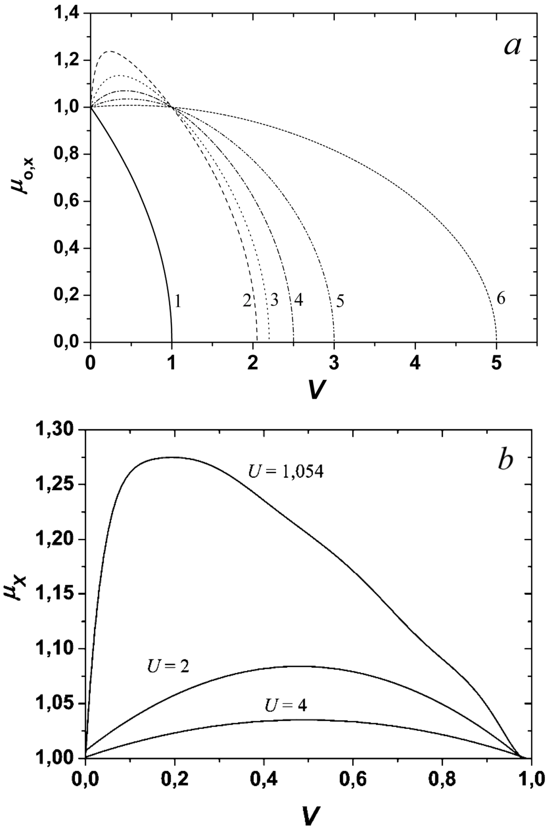

Fig. 1. Dependences of the refractive index on V (a) for the ordinary wave (curve *1*) and the extraordinary wave at $U = 1.1$, 1.2, 1.5, 2, and 4 (curves *2* to *6*, respectively) and (b) for the extraordinary wave in the interval of V from 0 to 1 at $U = 1.054$, 2, and 4

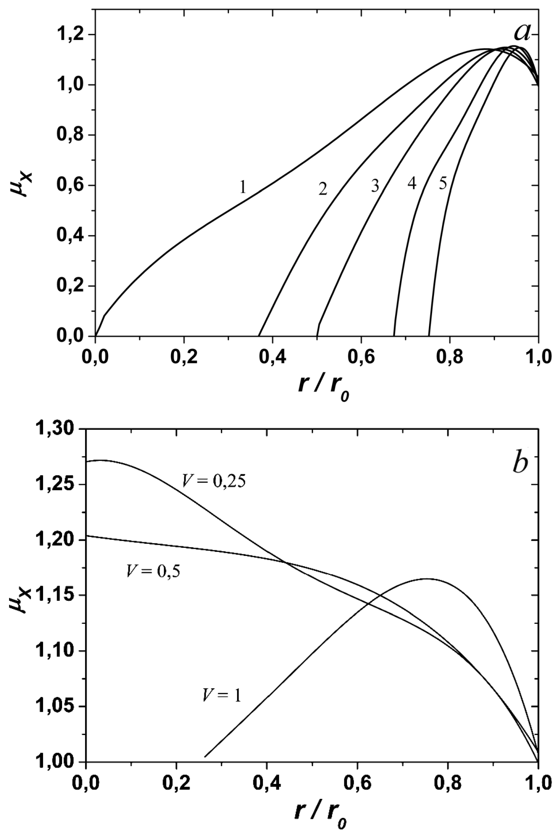

Fig. 2. Radial dependences of μ_x at the probing in an U-3M cross-section from the inner side (the higher magnetic field). $B = 0.72$ T, the probing frequency $f_0 = 18$ GHz, $N(r) = N_0[1 - (r/r_0)^2]$, N_0 is the plasma density at the magnetic axis, and $r = 19$ cm is the distance from the magnetic axis to the plasma boundary. Panel *a*: $V_0 = 2$, 3, 3.5, 4, and 5 (curves *1* to *5*, respectively); panel *b*: $V_0 = 0.25$. 0.5, and 1

across the external magnetic field follow from the dependence of the wave refractive index on the magnetic field and the plasma density (Fig. 1),

$$\mu_x = \left[\frac{U^2 - (1-V)^2}{U^2 - (1-V)}\right]^{1/2}, \tag{1}$$

where $U = (f_{ce}/f_0)$; $V = (N(r)/N_{\rm cr})$; $N(r)$ and $N_{\rm cr}$ are the density and the critical density, respectively, for the probing frequency f_0; and r is the plasma radius. The function $\mu_x(V)$ grows with the density and attains a maximum at

$$V = -\left(U^2 - 1\right) + \sqrt{U^2\left(U^2 - 1\right)}. \tag{2}$$

Then it decreases down to zero and reaches it at $V \to 1 + U$. At $V = 1$, we have $\mu_x(V) = 1$. The radial dependence of the refractive index along the plasma probing chord in a cross-section of a U-3M torsatron, which is perpendicular to its axis, from the inner side (a higher magnetic field) is depicted in Fig. 2 for $B_0 = 0.72$ T, $f_0 = 18$ GHz, and $N_{\rm cr} = 4.02 \times 10^{12}$ cm^{-3}. However, while probing the plasma in a torsatron, it should be taken into account that the direction of the total magnetic field does not coincide with that of the torsatron axis, deviating by the angle $\psi = \arctan(\xi_h/(1+\xi_t))$, where ξ_h and ξ_t are the coefficients of poloidal and toroidal, respectively, non-uniformity of the magnetic field [9]. At $\psi < 0.1\pi$,

$$\mu_x = \left[\frac{U^2\cos^2\psi - (1-V)^2}{U^2\cos^2\psi - (1-V)}\right]^{1/2}. \tag{3}$$

In Fig. 3, the dependences of the quantities U, V, and the angle ψ on the distance from the plasma boundary are shown. The figure also illustrates the influence of the angle ψ on the refractive index. Two sections should be distinguished in the plot of the function $\mu_x(V)$: the first one extends from the plasma boundary to a layer, in which $V = 1$; the second covers the interval where $1 < V < 1 + U$. The parameter $\mu_x > 1$ in the first section, and $\mu_x < 1$ in the second one. If the maximum density is lower than $V = 1 + U$, then, taking into account that the phase shift of a wave is proportional to $1 - \mu_x$, the phase shift of the extraordinary wave changes from negative to positive at its transition from one region to the other one (see Fig. 4). The point of the sign change at the transition corresponds to $V = 1$. If the plasma layer is opaque, the change of the phase sign does not manifest itself at the reflection. It is also worth noting that, if the parameter U passes through 1 in a non-uniform magnetic field, the reflection condition changes from $V = 1 + U$ to $V = 1 - U$ or *vice versa* ($U < 1$). If U approaches 1 from above, the maximum of μ_x shifts toward $V = 0$ in accordance with formula (2), and $\mu_x = 0$ at $V = 2$ (see Fig. 1). In a vicinity of $U = 1$, the dependence of the cut-off density on U has a discontinuity: it tends linearly to zero at $U < 1$ and linearly grows from 2 to $1 + U$ at $U > 1$. At $U < 1$, the dependence $\mu_x(V)$ is not continuous, because the interval from $V = 1 - U$ to $V = 1 - U^2$ is opaque. This property creates certain restrictions on the extraordinary wave applications to reflectometry. If the magnetic field slightly changes along the measurement region, it is expedient to use the probing frequency f_0 that is lower than the minimal f_{ce}-value. It is also expedient to use the average value of U along the probing chord rather than its local values (Fig. 5).

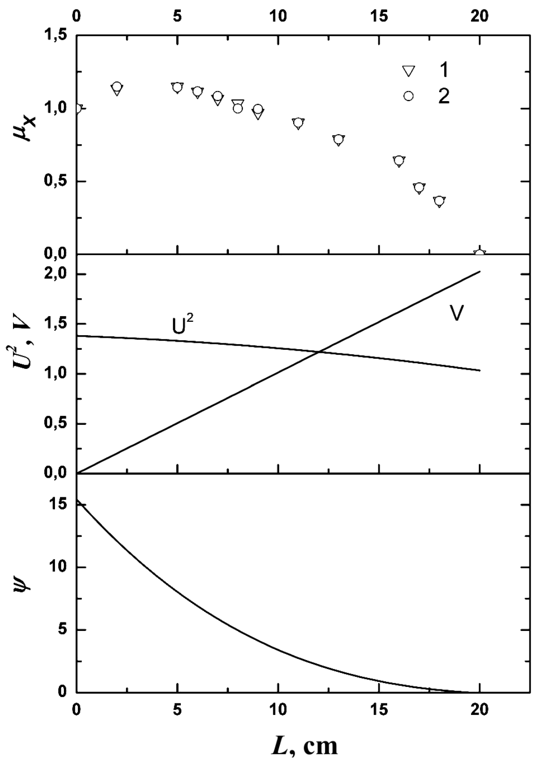

Fig. 3. Dependences (upper panel) $\mu_x(L)$ at the normal beam incidence on plasma (*1*) and at the angle ψ (2), (middle panel) $U^2(L)$ and $V(L)$,and (bottom panel) $\psi(L)$. L is the distance from the plasma boundary; $f_0 = 18$ GHz, $N_{\rm cr} = 4.02 \times 10^{12}$ cm^{-3}, and $N_0 = N_{\rm cr}(1 + U)$

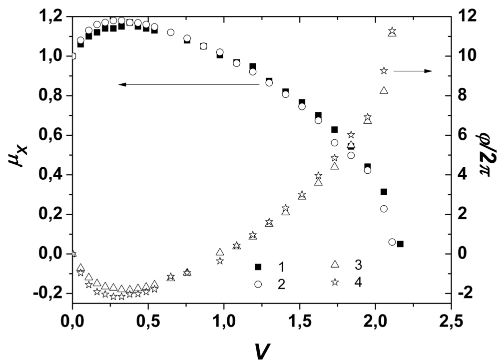

Fig. 4. V-dependences of the refractive index for the X-wave (curves *1* and *2*) and the phase shift (curves *3* and *4*) at plasma interferometry: the value $U^2 = 1.3$ at the internal plasma boundary (*1* and *3*) and the average value along the probing chord (*2* and *4*)

3. Oblique Probing with an Extraordinary Wave

In some cases, the oblique probing of plasma should be used. The oblique probing with the use of ordinary and extraordinary waves allows the spatial distributions of the plasma density and the magnetic field induction to be determined. In work [11], the peculiarities in the extraordinary wave refraction were studied, and the spatial distributions of the density and the magnetic field were calculated.

The oblique probing is also used in Doppler reflectometry used to diagnose a lot of plasma characteristics and to determine the dispersion dependences

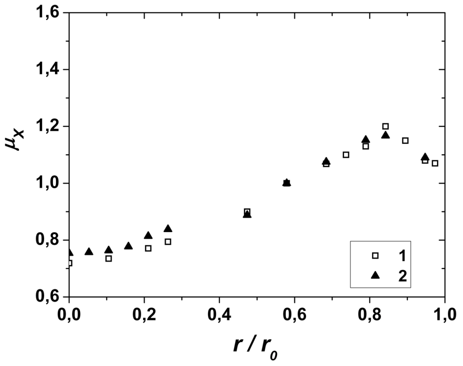

Fig. 5. Radial dependences of the refractive index for the X-wave (*1*) with regard for the radial distribution of a magnetic field and (*2*) if the local values of a magnetic field are substituted by its average value along the probing path

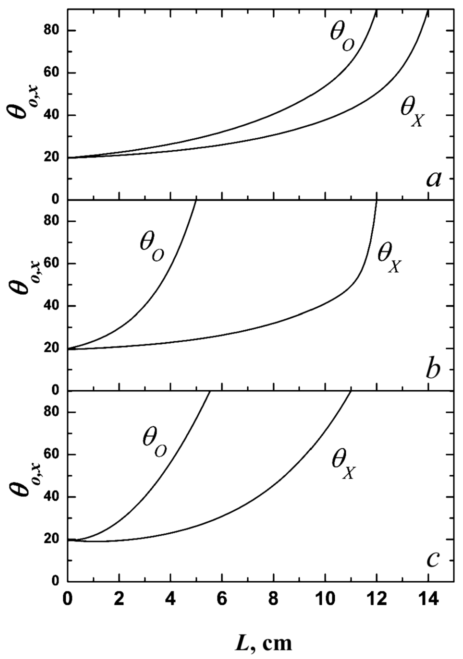

Fig. 6. Relations between the angular beam shift and the distance from the plasma boundary for the ordinary and extraordinary waves at an entry angle into plasma of 20° and for $V = 0.25$ (*a*), 1 (*b*), and 2 (*c*)

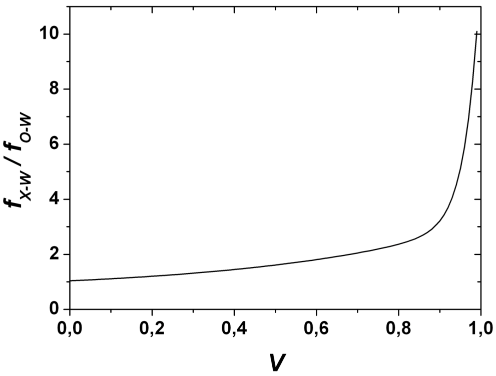

Fig. 7. Dependence of the ratio between Doppler frequency shifts for the extraordinary and ordinary waves on V

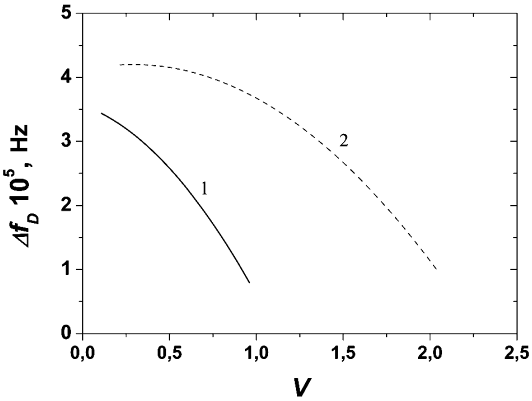

Fig. 8. Dependences of the frequency shift for the ordinary (*1*) and extraordinary (*2*) waves on V

$\omega(k)$, the spatial distributions of poloidal and radial motion velocities of a plasma layer and the electric field, and the velocity and electric field shears [1, 12]. In this method, when $\mu_x > 1$, the inclination angle diminishes, and the refraction becomes negative. At the oblique probing of plasma, the plasma density is lower than the critical one at the point of the backward beam scattering, and it can be determined from the relation

$$r_0 \sin\theta_0 = r_1 \mu_x^{(1)} \sin\theta_1 = ... = r_k \mu_x^{(k)} \sin\theta_k. \quad (4)$$

Using Eq. (4), it is possible to reproduce the beam path, i.e. the angle variation at a growth of the distance from the plasma boundary, bearing in mind that $\theta_{o,x} = 90°$ at the reflection point (Fig. 6). Note that if $f_0 < f_{ce}$, the extraordinary wave beam penetrates more deeply into plasma and deviates less from the initial direction in comparison with the ordinary wave. At $\mu_x > 1$, the angle θ_i becomes smaller than θ_0, i.e. the negative refraction takes place.

On the basis of the Doppler effect at the oblique probing, we developed a method of determination of the angular and linear rotational velocities of plasma layers. In order to determine the Doppler shift of the frequency, the probing wave is directed at a certain angle to the normal at the incidence point on the plasma boundary, where it is reflected according to Eq. (4). If there are fluctuations in the plasma layer, this layer serves as a reflecting diffraction grating. According to the Bragg principle, the reflected beams of various diffraction orders differ by their frequencies and satisfy the Bragg diffraction equation [7, 8]

$$mk = k_0\,(\sin\theta_i - \sin\theta_s), \tag{5}$$

where k is the wave number of fluctuations, m the diffraction order, k_0 the wave number of a probing wave, and θ_i and θ_s are the incidence and scattering angles, respectively.

The emitting antenna is inclined with respect to the reflecting layer in accordance with Eq. (5), and it can receive the reflected beam of the (-1)-th diffraction order, which is characterized by a frequency shifted relative to the probing one and an amplitude much smaller than that of the incident wave. The wave number of the reflected signal of the (-1)-th diffraction order equals $K_f = -2k\sin\theta_0$. The frequency shift for the reflected signal equals

$$\Delta f_{\theta_i} = -\frac{2f_0}{c}\mu_{o,x}(r_{\rm ref})v_p, \tag{6}$$

where θ_i is the wave incidence angle, and $\mu_{o,x}$ and v_p are the refractive indices and the rotational velocity of the reflecting layer of the radius $r_{\rm ref}$, respectively. Taking into account that the Doppler shift is proportional to the velocity and the refractive index, we obtain that, provided the same velocity, the larger the refractive index, the larger is the frequency shift. Hence, a comparison between the frequency shifts for the X- and O-waves shows that the ratio between the Doppler frequency shifts, $\frac{f_d(X-W)}{f_d(O-W)} = \frac{\mu_x}{\mu_O} > 1$, strongly increases in a vicinity of $V = 1$ (Figs. 7 and 8). The oblique probing with the use of X-waves allows the layers with the density $(1+V)$ times higher than the critical one to be studied. In order to determine the rotational velocity in an arbitrary layer, one should measure the shift of Δf on Eq. (6), calculate the density $N(r)$ in the reflection layer on the basis of phase reflectometry results, and, taking the known dependence $B(r)$ into account, calculate $\mu_x(r)$ from Eq. (1) and the reflection radius from the relation $r_{\rm ref} = r_0\sin\theta_0/\mu_x(r_{\rm ref})$.

For the beam to be reflected in a layer with the given value $\mu_x(r)$, the required incidence angle can be determined from Eq. (4) as $\Phi = \arcsin\left(\frac{\mu_x(r)}{r_0}\right)$ taking into account that $\theta_{o,x} = 90^\circ$ at reflection.

It is worth noting that the beam width, as well as the steepnesses of the wave front and the reflecting layer, induces a broadening of the spectrum of wave numbers according to the formula [10]

$$\Delta k = \frac{2^{3/2}}{w\left[1 + \left(w^2\frac{k_0}{\rho}\right)^2\right]^{1/2}}, \tag{7}$$

where w is the microwave beam width, $w = 2$ cm, k_0 the wave number, and ρ the steepness radius of the reflecting layer. For instance, for the torsatron U-3M, we have $k_0 = 2$ cm^{-1} and $\rho = 2$ cm; therefore, the width of the spectrum of wave numbers for the scattered signal equals $\Delta k = 1$ cm^{-1}.

4. Conclusions

UHF reflectometry with the use of extraordinary waves with the frequency $f_0 < f_{ce}$ has the following advantages:

– the transparency interval broadens out to a density that does not exceed the value of $N_{\rm cr}(1+U)$;

– the oblique probing with the use of either an ordinary or an extraordinary wave allows the profiles of the plasma density and the magnetic field to be determined by varying the angle, at which the beam enters into plasma;

– for identical entering angles, the extraordinary wave reaches layers with higher densities;

– at Doppler reflectometry, the frequency shift for the extraordinary wave is larger than that for the ordinary one, provided the same angle.

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НВЧ-РЕФЛЕКТОМЕТРІЯ ПЛАЗМИ НЕЗВИЧАЙНОЮ ХВИЛЕЮ З ЧАСТОТОЮ, МЕНШОЮ ВІД ЕЛЕКТРОННО-ЦИКЛОТРОННОЇ

Р е з ю м е

Одержано порівняльні залежності коефіцієнтів заломлення звичайної і незвичайної хвиль від профілів густини плазми і магнітного поля при різних умовах зондування. Проаналізовані можливі переваги від використання для діагностики магнітоактивної плазми незвичайної хвилі з частотою, меншою від циклотронної частоти електронів, враховані особливості зондування плазми на торсатроні У-3М. Досліджено рефракцію мікрохвильового потоку при похилому зондуванні плазми, враховано вплив полоїдальної складової магнітного поля. Встановлено, що величина допплерівського зсуву частоти незвичайної хвилі при відбитті від рухомого шару плазми перевищує відповідний зсув звичайної хвилі.