DISPERSION RELATIONS FOR FIELD-ALIGNED CYCLOTRON WAVES IN AN AXISYMMETRIC TOKAMAK PLASMA WITH ANISOTROPIC TEMPERATURE

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Dispersion equations are evaluated for field-aligned cyclotron waves in axisymmetric tokamak plasmas with circular magnetic surfaces. Bi-Maxwellian distribution function is used to model the energetic particles (ions or electrons) with anisotropic temperature. The growth/damping rate of cyclotron waves in tokamaks is defined by the contributions of the resonant trapped and untrapped particles to the imaginary part of the transverse susceptibility elements.

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1. INTRODUCTION

As is well known, the temperature anisotropy generated by cyclotron resonance heating of magnetized plasmas can be a reason of cyclotron wave instabilities in considered plasma devises. Recently [1], an anisotropic ion temperature was measured during high power HHFW heating in helium plasmas on the National Spherical Torus Experiment, with the transverse ion temperature roughly twice the parallel ion temperature. Moreover, the measured spectral distribution suggested that two populations of cold and hot ions are present in the plasma. In the paper [2], it was shown that wave plasma interactions play an important role in tokamak dynamics. In particular, the fast ions from neutral beam injection can excite compressional and global Alfven eigenmodes with frequencies near the fundamental ion cyclotron frequency, and "slow waves" appear to propagate along the equilibrium magnetic field. However, two-dimensional (2D) kinetic wave theory in tokamaks should be based on the solution of Maxwell's equations using the correct 'kinetic' dielectric tensor. In this paper we evaluate the dispersion equations for field-aligned cyclotron waves in tokamaks with circular magnetic surfaces, having the high-energy particles with anisotropic temperature. The main contributions of the untrapped and trapped particles to the transverse dielectric tensor elements are derived by solving the linearized Vlasov equations for their perturbed distribution functions.

2. REDUCED VLASOV EQUATION

To describe a 2D axisymmetric tokamak with circular magnetic surfaces we use the quasi-toroidal coordinates (r,θ,ϕ) connected with cylindrical ones (ρ,ϕ,z) as $\rho = R_0 + r\cos\theta$, $z = -r\sin\theta$, $\phi = \phi$, where R_0 is the large torus radius, r is the small plasma radius, θ is the poloidal angle, ϕ is the toroidal angle. In this case, the stationary magnetic field components, $\mathbf{H}_0 = \{0, H_{0\theta}, H_{0\phi}\}$, are

$$H_{0\theta} = \frac{\overline{H}_{0\theta}(r)}{1+\varepsilon\cos\theta}, \quad H_{0\phi} = \frac{\overline{H}_{0\phi}(r)}{1+\varepsilon\cos\theta}, \quad \mathbf{h} = \frac{\mathbf{H}_0}{H_0} = \{0, h_\theta, h_\phi\}$$

To evaluate the transverse susceptibility elements we should know the first ($l = \pm 1$) harmonics of the perturbed distribution function,

$$f(t,\mathbf{r},\mathbf{v}) = \sum_s^{\pm 1}\sum_l^{\pm\infty} f_l^s(r,\theta,v,\mu)\exp(-i\omega t + in\phi - il\sigma),$$

where the new variables (v,μ) are introduced instead of $(v_\parallel, v_\perp)$ in velocity space as

$$v = \sqrt{v_\parallel^2 + v_\perp^2}, \qquad \mu = v_\perp^2(1+\varepsilon\cos\theta)/v^2.$$

The linearized Vlasov equation for $f_1^{(s)}$ and $f_{-1}^{(s)}$ in the zero-order of magnetization parameters can be reduced to:

$$\frac{\partial f_l^{(s)}}{\partial\theta} + ik_l^{(s)}(\theta,r,v,\mu)f_l^{(s)} = Q_l^{(s)}, \quad s=\pm 1, \; l=\pm 1. \quad (1)$$

where

$$k_l^{(s)} = \frac{nq}{1+\varepsilon\cos\theta} + \frac{lh_\phi}{2}\left(\frac{4+\varepsilon\cos\theta}{1+\varepsilon\cos\theta} - \frac{r}{q}\frac{\partial q}{\partial r}\right) - \frac{sr\left(\omega - \frac{l\,\Omega_{c0}}{1+\varepsilon\cos\theta}\right)}{h_\theta v\sqrt{1-\frac{\mu}{1+\varepsilon\cos\theta}}}$$

$$Q_l^{(s)} = \frac{s\,e\,r}{2T_\parallel h_\theta}\sqrt{\frac{\mu}{1+\varepsilon\cos\theta-\mu}}F_0\left\{\left[1-\left(1-\frac{T_\parallel}{T_\perp}\right)\left(1+\varepsilon\cos\theta\right)\right]E_l + s\left(1-\frac{T_\parallel}{T_\perp}\right)\frac{v}{c}\left(1+\varepsilon\cos\theta\right)\sqrt{1-\frac{\mu}{1+\varepsilon\cos\theta}}H_l\right\},$$

$$F_0 = \frac{N_0(r)}{\pi^{1.5}v_{T\perp}^2 v_{T\parallel}}\exp\left(-\frac{v^2}{v_{T\parallel}^2}\left(1-\mu\left(1-\frac{T_\parallel}{T_\perp}\right)\right)\right),$$

$$v_{T\parallel}^2 = \frac{2T_\parallel}{M}, \quad v_{T\perp}^2 = \frac{2T_\perp}{M}, \quad q = \frac{rh_\phi}{R_0 h_\theta}, \quad \varepsilon = \frac{r}{R_0},$$

$$\Omega_{c0} = \frac{e\sqrt{\overline{H}_{0\theta}^2 + \overline{H}_{0\phi}^2}}{Mc}, \quad E_l = E_n + ilE_b, \quad H_l = H_b - ilH_n.$$

Here F_0 is the bi-Maxwellian distribution function of particles with density N_0, mass M, charge e, parallel and transverse temperatures $T_\parallel$ and $T_\perp$. By $E_{\pm 1} = E_n \pm iE_b$ we describe the transverse electric field components with the left- and right-hand polarization, where E_n and E_b are the normal and binormal perturbed **E**-field components relative to $\mathbf{H}_0$. By $s = \pm 1$ we distinguish the particles with positive and negative parallel velocity relatively $\mathbf{H}_0$.

To simplify a problem, we solve Eqs. (1) using the set of coordinates, where the $\mathbf{H}_0$-field lines are 'straight', introducing the new poloidal angle as

$$\overline{\theta}(\theta) = 2\,\mathrm{arctg}\left(\sqrt{\frac{1-\varepsilon}{1+\varepsilon}}\,\mathrm{tg}\frac{\theta}{2}\right),$$

accounting for the approximated connection for field-aligned waves:

$$H_l \approx -i\frac{c}{\omega}\frac{(1-\varepsilon\cos\overline{\theta})^2}{\sqrt{1-\varepsilon^2}}\frac{h_\theta}{r}\left(\frac{\partial}{\partial\overline{\theta}} + inq_t\right)\frac{E_l}{1-\varepsilon\cos\overline{\theta}}.$$

Since our plasma model is a configuration with one minimum of $\mathbf{H}_0$, the plasma particles should be separated in the two populations of the trapped and untrapped particles:

1) $0 \le \mu \le 1-\varepsilon$, $-\pi \le \overline{\theta} \le \pi$ for untrapped particles, and

2) $1-\varepsilon \le \mu \le 1+\varepsilon$, $-\theta_t \le \overline{\theta} \le \theta_t$ for trapped particles,

where $\quad \pm\theta_t = \pm 2\arcsin\sqrt{\dfrac{(1-\varepsilon)(1+\varepsilon-\mu)}{2\varepsilon\mu}}$

are the reflection points of trapped particles, by the zeros of parallel velocity: $v_\parallel = 0$. As a result,

$$f_l^{(s)}(r,\overline{\theta},v,\mu) = f_{l,u}^{(s)}\big|_{0\le\mu\le 1-\varepsilon} + f_{l,t}^{(s)}\big|_{1-\varepsilon\le\mu\le 1+\varepsilon},$$

where the indexes u and t correspond to the untrapped and trapped particles, respectively.

To describe the bounce-periodic motion of the u- and t-particles along the $\mathbf{H}_0$-field line, it is convenient to introduce the new time-like variables instead of $\overline{\theta}$:

$$\tau_u(\overline{\theta}) = \int_0^{\overline{\theta}/2}\frac{d\eta}{(1+\kappa_o\sin^2\eta)\sqrt{1-\kappa^2\sin^2\eta}} = \Pi\left(\frac{\overline{\theta}}{2},\kappa_o,\kappa\right),$$

$$\tau_t(\overline{\theta}) = \Pi\left(\arcsin\left(\frac{1}{\widetilde{\kappa}}\sin\frac{\overline{\theta}}{2}\right),\kappa_o\widetilde{\kappa}^2,\widetilde{\kappa}\right),$$

where

$$\kappa = \sqrt{\frac{2\varepsilon\mu}{(1-\varepsilon)(1+\varepsilon-\mu)}},\quad \widetilde{\kappa} = \frac{1}{\kappa},\quad \kappa_o = \frac{2\varepsilon}{1-\varepsilon}.$$

After solving Eqs. (1), the 2D transverse (relative to $\mathbf{H}_0$) current density components, $j_{\pm 1}$, can be found as

$$j_{(\pm 1)}(r,\overline{\theta}) = j_{(\pm 1),u}(r,\overline{\theta}) + j_{(\pm 1),t}(r,\overline{\theta}),$$

where

$$j_{l,u} = \frac{\pi e\left(1-\varepsilon\cos\overline{\theta}\right)^{1.5}}{2(1-\varepsilon^2)}\sum_s^{\pm 1}\int_0^\infty v^3\int_0^{1-\varepsilon}\frac{f_{l,u}^{(s)}(r,\overline{\theta},v,\mu)\sqrt{\mu}\,d\mu dv}{\sqrt{1-\varepsilon^2-\mu(1-\varepsilon\cos\overline{\theta})}},$$

$$j_{l,t} = \frac{\pi e\left(1-\varepsilon\cos\overline{\theta}\right)^{1.5}}{2(1-\varepsilon^2)}\sum_s^{\pm 1}\int_0^\infty v^3\int_{1-\varepsilon}^{\frac{1-\varepsilon^2}{1-\varepsilon\cos\overline{\theta}}}\frac{f_{l,t}^{(s)}(r,\overline{\theta},v,\mu)\sqrt{\mu}\,d\mu dv}{\sqrt{1-\varepsilon^2-\mu(1-\varepsilon\cos\overline{\theta})}}.$$

3. DISPERSION EQUATIONS

To evaluate the dielectric tensor elements we use the Fourier expansions of the 2D perturbed electric field and current density components:

$$\frac{\mathbf{j}(r,\overline{\theta})}{1-\varepsilon\cos\overline{\theta}} = \sum_m^{\mp\infty}\mathbf{j}^{(m)}e^{im\overline{\theta}},\quad \frac{\mathbf{E}(r,\overline{\theta})}{1-\varepsilon\cos\overline{\theta}} = \sum_{m'}^{\mp\infty}\mathbf{E}^{(m')}e^{im'\overline{\theta}}.$$

As a result,

$$\frac{4\pi i}{\omega}j_{(l)}^{(m)} = \sum_{m'}^{\pm\infty}\left[\chi_{l,u}^{m,m'} + \chi_{l,t}^{m,m'}\right]\left[\mathring{A}_n^{(m')} + il\mathring{A}_b^{(m')}\right],$$

$l = \pm 1$.

Here $\chi_{l,u}^{m,m'}$ and $\chi_{l,t}^{m,m'}$ are the contribution of u- and t-particles to the transverse susceptibility elements:

$$\chi_{l,u}^{m,m'} = \frac{4\omega_p^2 r\sqrt{1+\varepsilon}}{\pi^{2.5}\omega h_\theta v_{T\parallel}\sqrt{1-\varepsilon}}\frac{T_\parallel}{T_\perp}\times$$

$$\times\sum_p^{\pm\infty}\int_0^1\frac{\kappa^3 d\kappa}{(\kappa_o+\kappa^2)^2}\int_{-\infty}^{\infty}\frac{\exp\left[-u^2\left(1-\frac{\kappa^2(1+\varepsilon)}{\kappa_o+\kappa^2}\left(1-\frac{T_\parallel}{T_\perp}\right)\right)\right]}{(p+nq_t+l\xi+l\varsigma)u - U_l(\kappa)}\times$$

$$\times u^4\overline{A}_{p,l}^m(u,\kappa)A_{p,l}^{m'}(u,\kappa)du, \qquad (2)$$

$$\chi_{l,t}^{m,m'} = \frac{4\omega_p^2 r\sqrt{1+\varepsilon}}{\pi^{2.5}\omega h_\theta v_T\sqrt{1-\varepsilon}}\frac{T_\parallel}{T_\perp}\times$$

$$\times\sum_p^{\pm\infty}\int_0^1\frac{\widetilde{\kappa}\;d\widetilde{\kappa}}{(1+\kappa_o\widetilde{\kappa}^2)^2}\int_{-\infty}^{\infty}\frac{\exp\left[-u^2\left(1-\frac{1+\varepsilon}{1+\kappa_o\widetilde{\kappa}^2}\left(1-\frac{T_\parallel}{T_\perp}\right)\right)\right]}{pu - V_l(\widetilde{\kappa})}$$

$$\times u^4\overline{B}_{p,l}^m(u,\widetilde{\kappa})B_{p,l}^{m'}(u,\widetilde{\kappa})du, \qquad (3)$$

where

$$A_{p,l}^m(u,\kappa) = \int_0^{\pi/2}\cos\left(\Psi_{p,l}^m(u,\kappa,\eta)\right)\sqrt{\frac{1+\kappa_o\sin^2\eta}{1-\kappa^2\sin^2\eta}}\times$$

$$\times\left\{1-\left(1-\frac{T_\parallel}{T_\perp}\right)\frac{1+\varepsilon}{1+\kappa_o\sin^2\eta}+\right.$$

$$\left.+\left(1-\frac{T_\parallel}{T_\perp}\right)\frac{k_{\parallel,m}uv_{T\parallel}\sqrt{2\varepsilon(1+\varepsilon)}}{\omega\sqrt{\kappa_o+\kappa^2}}\sqrt{1-\kappa^2\sin^2\eta}\right\}d\eta,$$

$$\overline{A}_{p,l}^m(u,\kappa) = \int_0^{\pi/2}\cos\left(\Psi_{p,l}^m(u,\kappa,\eta)\right)\sqrt{\frac{1+\kappa_o\sin^2\eta}{1-\kappa^2\sin^2\eta}}d\eta,$$

$$B_{p,l}^m(u,\widetilde{\kappa}) = \int_0^{\pi/2}\cos\left(\Phi_{p,l}^m(u,\widetilde{\kappa},\eta)\right)\sqrt{\frac{1+\kappa_o\widetilde{\kappa}^2\sin^2(\eta)}{1-\widetilde{\kappa}^2\sin^2(\eta)}}\times$$

$$\times\left\{1-\left(1-\frac{T_\parallel}{T_\perp}\right)\frac{1+\varepsilon}{1+\kappa_o\widetilde{\kappa}^2\sin^2\eta}+\right.$$

$$\left.+\left(1-\frac{T_\parallel}{T_\perp}\right)\frac{k_{\parallel,m}uv_{T\parallel}\sqrt{2\varepsilon(1+\varepsilon)}}{\omega\sqrt{1+\kappa_o\widetilde{\kappa}^2}}\widetilde{\kappa}\cos\eta\right\}d\eta,$$

$$+(-1)^p\int_0^{\pi/2}\cos\left(\Phi_{-p,l}^m(-u,\widetilde{\kappa},\eta)\right)\sqrt{\frac{1+\kappa_o\widetilde{\kappa}^2\sin^2(\eta)}{1-\widetilde{\kappa}^2\sin^2(\eta)}}\times$$

$$\times\left\{1-\left(1-\frac{T_\parallel}{T_\perp}\right)\frac{1+\varepsilon}{1+\kappa_o\widetilde{\kappa}^2\sin^2\eta}+\right.$$

$$\left.+\left(1-\frac{T_\parallel}{T_\perp}\right)\frac{k_{\parallel,m}uv_{T\parallel}\sqrt{2\varepsilon(1+\varepsilon)}}{\omega\sqrt{1+\kappa_o\widetilde{\kappa}^2}}\widetilde{\kappa}\cos\eta\right\}d\eta,$$

$$\overline{B}_{p,l}^m(u,\widetilde{\kappa}) = \int_0^{\pi/2}\cos\left(\Phi_{p,l}^m(u,\widetilde{\kappa},\eta)\right)\sqrt{\frac{1+\kappa_o\widetilde{\kappa}^2\sin^2(\eta)}{1-\widetilde{\kappa}^2\sin^2(\eta)}}d\eta,$$

$$\Psi_{p,l}^m(u,\kappa,\eta) = 2(m+nq_t+l\xi)\eta + 2l\varsigma\times$$

$$\times\mathrm{arctg}\left(\sqrt{\frac{1+\varepsilon}{1-\varepsilon}}\,\mathrm{tg}\,\eta\right) - (p+nq_t+l\xi+l\varsigma)\frac{\pi\Pi(\eta,\kappa_o,\kappa)}{\Pi\left(\frac{\pi}{2},\kappa_o,\kappa\right)}$$

$$+l\frac{\Omega_{c0}r\sqrt{2(\kappa_o+\kappa^2)}}{h_\theta uv_{T\parallel}\sqrt{\varepsilon(1+\varepsilon)}}\left[F(\eta,\kappa) - K(\kappa)\frac{\Pi(\eta,\kappa_o,\kappa)}{\Pi(\pi/2,\kappa_o,\kappa)}\right],$$

$$F(\eta,\kappa)=\int_0^\eta d\varphi/\sqrt{1-\kappa^2\sin^2\varphi}\,,\quad K(\kappa)=F\left(\frac{\pi}{2},\kappa\right),$$

$$\Phi_{p,l}^m(u,\tilde{\kappa},\eta)=2(m+nq_t+l\xi)\arcsin(\tilde{\kappa}\sin\eta)+$$

$$+\,2l\varsigma\,\mathrm{arctg}\left(\sqrt{\frac{1+\varepsilon}{1-\varepsilon}}\frac{\tilde{\kappa}\sin\eta}{\sqrt{1-\tilde{\kappa}^2\sin^2\eta}}\right)-\frac{p\pi\;\Pi\left(\eta,\kappa_o\tilde{\kappa}^2,\tilde{\kappa}\right)}{2\Pi\left(\pi/2,\kappa_o\tilde{\kappa}^2,\tilde{\kappa}\right)}+$$

$$+\,l\frac{\Omega_{c0}r\sqrt{2(1+\kappa_o\tilde{\kappa}^2)}}{h_\theta uv_{T\parallel}\sqrt{\varepsilon(1+\varepsilon)}}\left[F\left(\eta,\tilde{\kappa}\right)-K\left(\tilde{\kappa}\right)\frac{\Pi\left(\eta,\kappa_o\tilde{\kappa}^2,\tilde{\kappa}\right)}{\Pi\left(\frac{\pi}{2},\kappa_o\tilde{\kappa}^2,\tilde{\kappa}\right)}\right]$$

$$U_l(\kappa)=\frac{r\sqrt{2(\kappa_o+\kappa^2)}}{\pi h_\theta v_T\sqrt{\varepsilon(1+\varepsilon)}}\times$$
$$\times\left[\omega(1+\varepsilon)\Pi\left(\pi/2,\kappa_o,\kappa\right)-l\Omega_{c0}K(\kappa)\right],$$

$$V_l(\tilde{\kappa})=\frac{2r\sqrt{2(1+\kappa_o\tilde{\kappa}^2)}}{\pi h_\theta v_T\sqrt{\varepsilon(1+\varepsilon)}}\times$$
$$\times\left[\omega(1+\varepsilon)\Pi\left(\pi/2,\kappa_o\tilde{\kappa}^2,\tilde{\kappa}\right)-l\Omega_{c0}K(\tilde{\kappa})\right],$$

$$X(\bar{\theta})\equiv\arcsin\left(\frac{1}{\tilde{\kappa}}\sin\left(\frac{\bar{\theta}}{2}\right)\right),\qquad q_t\equiv\frac{q}{\sqrt{1-\varepsilon^2}}\,,$$

$$\omega_p^2=\frac{4\pi N_0e^2}{M},\quad \xi=\frac{1.5h_\phi}{\sqrt{1-\varepsilon^2}},\quad \varsigma=\frac{h_\phi}{2}\left(1-\frac{r}{q}\frac{dq}{dr}\right).$$

To have analogy with the linear theory of cyclotron waves in the straight magnetic field let us assume that the $E_{\pm1}^{(m)}$-harmonics of **E**-field gives the main contribution to $j_{\pm1}^{(m)}$. In this case, for the field-aligned cyclotron waves with given mode number *m*, we get the following dispersion equation from the Maxwell's equations:

$$\frac{k_{\parallel,m}^2}{\omega^2}c^2=1+2\sum_{\alpha}^{e,i_1,i_2,\ldots}\left(\chi_{l,u,\alpha}^{m,m}+\chi_{l,t,\alpha}^{m,m}\right),\qquad(4)$$

where α denotes the particle species (electron, proton, heavy ions), $k_{||,m}=(m+nq_t)h_\theta/r$. Further, Eq. (4) should be resolved numerically for the real and imaginary parts of the wave frequency, $\omega=\mathrm{Re}\omega+i\,\mathrm{Im}\omega$, to define the conditions of the wave instabilities in the tokamak plasmas with anisotropic temperature. As usual, the growth (damping) rate of the cyclotron waves, $\mathrm{Im}\,\omega$, is defined by the contribution of the resonant particles to the imaginary part of the transverse susceptibility elements:

$$\mathrm{Im}\,\chi_{l,(\alpha)}^{m,m}=\sum_{p=1}^{\infty}\left(\mathrm{Im}\,\chi_{l,p,u,\alpha}^{m,m}+\mathrm{Im}\,\chi_{l,p,t,\alpha}^{m,m}\right),$$

where $\mathrm{Im}\chi_{l,p,u,\alpha}^{m,m}$ and $\mathrm{Im}\,\chi_{l,p,t,\alpha}^{m,m}$ are the separate contributions of the bounce resonance terms to $\mathrm{Im}\chi_{l,(\alpha)}^{m,m}$ for untrapped and trapped particles.

CONCLUSIONS

In conclusion, let us summarized the main results of the paper. The dispersion equations are derived for waves in the frequency range of the fundamental ion-cyclotron (*l*=1) and electron-cyclotron (*l*=-1) resonances and suitable to analyze the excitation/dissipation of both the left-hand (ion-cyclotron) and right-hand (electron-cyclotron) polarized waves. Contribution of *u*- and *t*-particles to the transverse susceptibility elements in 2D toroidal plasmas with anisotropic temperature are expressed by summation of the bounce-resonant terms including the double integration in velocity space, resonant denominators, and corresponding phase coefficients. Due to 2D $\mathbf{H_0}$-field nonuniformity, the bounce resonance conditions for trapped and untrapped particles in tokamaks are different from ones in the straight magnetic field; the whole spectrum of electric field is present in the given current density harmonic; the left-hand and right-hand polarized waves are coupled in the general case. As in the uniform magnetic field case, the growth/damping rate of the cyclotron waves in the 2D tokamaks is defined by the contribution of the energetic trapped and untrapped particles to the imaginary part of the transverse susceptibility elements.

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ДИСПЕРСИОННЫЕ УРАВНЕНИЯ ЦИКЛОТРОННЫХ ВОЛН ВДОЛЬ МАГНИТНОГО ПОЛЯ В ПЛАЗМЕ АКСИАЛЬНО-СИММЕТРИЧНЫХ ТОКАМАКОВ С АНИЗОТРОПНОЙ ТЕМПЕРАТУРОЙ

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Получены дисперсионные уравнения для циркулярно-поляризованных волн, распространяющихся вдоль магнитного поля в плазме аксиально-симметричного токамака круглого сечения. В качестве модельного распределения энергичных частиц по скоростям использована бимаксвелловская функция с анизотропной температурой. Показано, что инкремент/декремент циклотронных волн в аксиально-симметричных токамаках определяется вкладом резонансных пролетных и запертых частиц в мнимую часть поперечных компонент тензора диэлектрической восприимчивости.

ДИСПЕРСІЙНІ РІВНЯННЯ ЦИКЛОТРОННИХ ХВИЛЬ ВЗДОВЖ МАГНІТНОГО ПОЛЯ В ПЛАЗМІ АКСІАЛЬНО-СИМЕТРИЧНИХ ТОКАМАКІВ З АНІЗОТРОПНОЮ ТЕМПЕРАТУРОЮ

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Отримано дисперсійні співвідношення для циркулярно-поляризованих хвиль, що поширюються вздовж магнітного поля в плазмі аксіально-симетричних токамаків з коловим перерізом магнітних поверхонь. У якості модельного розподілу енергійних частинок у просторі швидкостей використана бімаксвелівська функція з анізотропною температурою. Доведено, що інкремент/декремент циклотронних хвиль в аксіально-симетричних токамаках визначається внеском резонансних пролітних та захоплених частинок в уявну частину поперечних компонент тензора діелектричної сприйнятливості.