FIELD-ALIGNED ELECTRON-CYCLOTRON WAVES IN A STRAIGHT MIRROR-TRAPPED PLASMA WITH ANISOTROPIC TEMPERATURE

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Dispersion characteristics have been analyzed for field-aligned electron-cyclotron waves (named also as the right-hand polarized or extraordinary waves) in a two-dimensional cylindrical magnetic mirror-trapped plasma including the electrons with anisotropic temperature (pressure). It is shown that the instability of these waves is possible only in the range below the minimal electron-cyclotron frequency, that much smaller than the gyrotron frequency used for ECR power input into the plasma, under the condition when the perpendicular temperature of resonant electrons is larger than their parallel temperature.

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INTRODUCTION

The recent plasma heating experiments in Gas-Dynamic Trap [1] by using high-frequency waves in the range of electron-cyclotron resonances (ECR) have demonstrated a tangible increase in electron temperature. Moreover, it was observed that such heating is accompanied by the development of low frequency instability. As an expected result, the ECR heating should lead to temperature anisotropy when the parallel temperature, $T_{\|h}$, is smaller than the perpendicular temperature, $T_{\perp h}$, of resonant (hot) electrons. On the other hand, the presence of electrons with $T_{\|h} < T_{\perp h}$ can cause the electron-cyclotron wave (ECW) instability and consequently affect the transport processes. To study the heating and stability problems in two-dimensional (2D) plasma models we should use the corresponding kinetic dielectric tensor [2], accounting for the cyclotron and bounce resonances. In this paper, we analyze the dispersion relations for field-aligned ECWs in a 2D cylindrical magnetic mirror-trapped plasma including electrons with anisotropic temperature.

1. PLASMA MODEL

Let us consider the simplest 2D collisionless mirror-trapped plasma suitable for cylindrical axisymmetric gas-dynamic open traps, where the confinement magnetic field can be approximated, Fig. 1, as

$$H_0(z) = \frac{H_{0min}}{1-\delta z^2 / L_0^2} . \qquad (1)$$

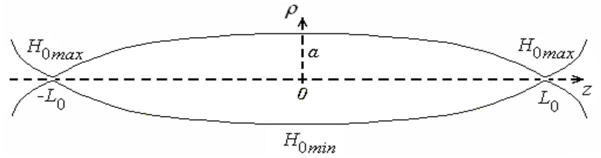

Fig. 1. Two-dimensional straight mirror-trapped magnetic field configuration

Here L_0 is the half length of mirror trap along the z-axis; $\delta = (R_m - 1)/R_m$; $R_m = H_{0max}/H_{0min}$ is the mirror ratio; H_{0min} is the minimal value of H_0 at the centre of the trap; H_{0max} is the maximum of H_0 at $z = \pm L_0$.

To simplify the calculations we assume that the radial magnetic field component is much smaller than the longitudinal one, which is valid for long mirror traps if $a/L_0 \ll 1/\sqrt{R_m}$, where a is the plasma radius at the central part of the trap (z=0). Thus, the radius of plasma boundary along the mirror trap is described by the following the law: $r_0(z) = a\sqrt{1-\delta z^2/L_0^2}$.

The steady-state distribution function of resonant (hot, h) electrons in velocity space is modeled by the bi-maxwellian distribution:

$$F_h = \frac{N_h}{\pi^{1.5} v_{T\|h} v_{T\perp h}^2} \exp\left\{ -\frac{v^2}{v_{T\|h}^2}\left[1-\mu\left(1-\frac{T_{\|h}}{T_{\perp h}}\right)\right]\right\}. \qquad (2)$$

Here the variables v (absolute value of velocity) and μ (non-dimensional magnetic moment) have been used instead of $v_\|$ and $v_\perp$ as

$$v = \sqrt{v_\|^2 + v_\perp^2} , \qquad \mu = \frac{v_\perp^2}{v_\|^2 + v_\perp^2}\left(1-\delta\frac{z^2}{L_0^2}\right); \qquad (3)$$

N_h is the density of resonant h-electrons; $v_{T\|h} = \sqrt{2T_{\|h}/m_e}$, $v_{T\perp h} = \sqrt{2T_{\perp h}/m_e}$ are their thermal velocities in the directions parallel and perpendicular relatively to $\mathbf{H}_0$, m_e is the mass of electrons. As far as the bulk (cold, c) electrons and plasma ions is concerned their distributions are the usual maxwellian with the low isotropic temperature, e.g., $T_{\|c} = T_{\perp c} = T_c$.

The main feature of a 2D mirror-trapped plasma is that the stationary magnetic field is axisymmetric and has one minimum at the centre of the trap. As a result, all the plasma particles should be separated in two groups of the so-called trapped and passing (untrapped) particles. In our case, such separation can be done by the non-dimensional parameters μ or $\kappa = \sqrt{1-\mu}$ analyzing the conditions when the parallel velocity of plasma particles is equal to zero:

$$v_\|(\kappa, z) = sv\sqrt{\frac{\kappa^2 - \delta z^2/L_0^2}{1-\delta z^2/L_0^2}} = 0 . \qquad (4)$$

Here we distinguish by the index $s = \pm 1$ the particles with the positive and negative parallel velocities relatively to $\mathbf{H}_0$. The domain of the perturbed distribution functions for the trapped particles is given [2] by the inequalities:

$$0 \le \kappa \le \sqrt{\delta} , \qquad -z_t(\kappa) \le z \le z_t(\kappa) , \qquad (5)$$

where $\pm z_t = \pm \kappa L_0 / \sqrt{\delta}$ are the stop points (or reflection points) of the trapped particles on the magnetic field line. As far as the untrapped particles is concerned, the corresponding domain of their distribution functions is defined as follows

$$\sqrt{\delta} \le \kappa \le 1, \qquad -L_0 \le z \le L_0 . \tag{6}$$

However, the influence of untrapped particles on the wave processes in the straight mirror-trapped plasmas is not substantial, since 1) they are lost in the one-half transit time, and 2) the number of passing particles is much smaller than the number of trapped particles if $R_m >> 1$. Further, we neglect the contribution of the untrapped particles to the current density components and, respectively, to the dielectric characteristics.

2. DISPERSION RELATIONS FOR ECWs

To draw analogy with the linear theory of ECWs in 1D straight magnetic field, let us assume that the n-th harmonic of the electric field gives the main contribution to the n-th harmonic of the current density [$\mathbf{E}(t,z), \mathbf{j}(t,z) \sim \exp(-i\omega t + inz/L_0)$]. In this case, for the field-aligned ECWs (when $E_\parallel = 0$, $H_\parallel = 0$) from the Maxwell's equations, we get the following dispersion equation [2]:

$$\left(\frac{\pi n c}{L_0 \omega}\right)^2 = 1 + 2\sum_{\alpha=c,h} \chi_{\perp,\alpha}^{n,n} , \tag{7}$$

where α denotes the particle species (e.g. the cold $\alpha = c$ and hot $\alpha = h$ electrons). As usual, the contributions of protons and heavy ions to this equation are negligible. The contribution of trapped electrons to the transverse elements of the dielectric susceptibility $\chi_{\perp,\alpha}^{n,n}$ in 2D mirror-trapped plasma is defined by the summation of bounce-resonant terms including the double integration in velocity space, resonant denominators and the phase coefficients:

$$\chi_{\perp,\alpha}^{n,n} = \frac{\Omega_{p\alpha}^2 L_0 T_{\parallel\alpha}^2}{\omega\delta\pi^{1.5} v_{T\parallel\alpha} T_{\perp\alpha}^2} \sum_{p=1}^{\infty} \int_{-\infty}^{\infty} u^4 du \int_0^{\sqrt{\delta}} A_{p,\alpha}^n(\kappa,u) B_{p,\alpha}^n(\kappa,u) \times$$
$$\times \frac{\exp\left\{-u^2\left[\kappa^2 + (1-\kappa^2)\dfrac{T_{\parallel\alpha}}{T_{\perp\alpha}}\right]\right\}}{pu - \dfrac{\omega E(\kappa) - \Omega_{c0} K(\kappa)}{\omega_{b,\alpha} E(\kappa)}} \kappa(1-\kappa^2) d\kappa . \tag{8}$$

Here, $\Omega_{p\alpha}^2 = \dfrac{4\pi N_\alpha e^2}{m_e}$; $\omega_{b\alpha}(\kappa) = \dfrac{\pi\sqrt{\delta} v_{T\parallel\alpha}}{2L_0 E(\kappa)}$ is the bounce-frequency of the trapped electrons with a longitudinal thermal velocity $v_{T\parallel\alpha} = \sqrt{2T_{\parallel\alpha}/m_e}$; $\Omega_{c0} = \dfrac{eH_{0min}}{m_e c}$ is the minimal electron gyrofrequency; $K(\kappa) = \int_0^{\pi/2} \dfrac{d\varphi}{\sqrt{1-\kappa^2\sin^2\varphi}}$, $F(\phi,\kappa) = \int_0^{\phi} \dfrac{d\varphi}{\sqrt{1-\kappa^2\sin^2\varphi}}$ and $E(\kappa) = \int_0^{\pi/2} \sqrt{1-\kappa^2\sin^2\varphi}\, d\varphi$, $E(\phi,\kappa) = \int_0^{\phi} \sqrt{1-\kappa^2\sin^2\varphi}\, d\varphi$ are the complete and non-complete elliptic integrals of the first and second kind, respectively;

$$A_{p,\alpha}^n(\kappa,u) = \int_0^{\pi/2} \left[1 - \frac{\pi n u v_{T\parallel\alpha} \kappa\cos\phi}{L_0\omega\sqrt{1-\kappa^2\sin^2\phi}}\left(1 - \frac{T_{\perp\alpha}}{T_{\parallel\alpha}}\right)\right] \times$$
$$\times \cos\left[n\pi\frac{\kappa}{\sqrt{\delta}}\sin\phi - p\pi\frac{E(\phi,\kappa)}{2E(\kappa)} + \right.$$
$$\left. + \frac{L_0\Omega_{c0}\langle F(\phi,\kappa)E(\kappa) - E(\phi,\kappa)K(\kappa)\rangle}{u v_{T\parallel\alpha}\sqrt{\delta} E(\kappa)}\right] d\phi +$$
$$+ (-1)^p \int_0^{\pi/2} \left[1 - \frac{\pi n u v_{T\parallel\alpha} \kappa\cos\phi}{L_0\omega\sqrt{1-\kappa^2\sin^2\phi}}\left(1 - \frac{T_{\perp\alpha}}{T_{\parallel\alpha}}\right)\right] \times$$
$$\times \cos\left[n\pi\frac{\kappa}{\sqrt{\delta}}\sin\phi + p\pi\frac{E(\phi,\kappa)}{2E(\kappa)} - \right.$$
$$\left. - \frac{L_0\Omega_{c0}\langle F(\phi,\kappa)E(\kappa) - E(\phi,\kappa)K(\kappa)\rangle}{u v_{T\parallel\alpha}\sqrt{\delta} E(\kappa)}\right] d\phi. \tag{9}$$

$$B_{p,\alpha}^n(\kappa,u) = \int_0^{\pi/2} \cos\left[n\pi\frac{\kappa}{\sqrt{\delta}}\sin\phi - p\pi\frac{E(\phi,\kappa)}{2E(\kappa)} + \right.$$
$$\left. + \frac{L_0\Omega_{c0}\langle F(\phi,\kappa)E(\kappa) - E(\phi,\kappa)K(\kappa)\rangle}{u v_{T\parallel\alpha}\sqrt{\delta} E(\kappa)}\right] d\phi +$$
$$+ (-1)^p \int_0^{\pi/2} \cos\left[n\pi\frac{\kappa}{\sqrt{\delta}}\sin\phi + p\pi\frac{E(\phi,\kappa)}{2E(\kappa)} - \right.$$
$$\left. - \frac{L_0\Omega_{c0}\langle F(\phi,\kappa)E(\kappa) - E(\phi,\kappa)K(\kappa)\rangle}{u v_{T\parallel\alpha}\sqrt{\delta} E(\kappa)}\right] d\phi . \tag{10}$$

When the denominator in $\chi_{\perp,\alpha}^{n,n}$ is equal to zero we get the conditions of the resonant interactions of ECWs with the trapped electrons in 2D straight mirror trap:

$$\omega - \Omega_{c0}\frac{K(\kappa)}{E(\kappa)} = \frac{p\pi v\sqrt{\delta}}{2L_0 E(\kappa)} , \qquad p = 0, \pm 1, \pm 2, \ldots, \tag{11}$$

which involve the wave frequency, the bounce-averaged cyclotron frequency and the bounce frequency, where the integer p is the number of the possible bounce-resonances. The trapped particles (both the cold and hot electrons) with the corresponding v and κ are named as resonant and responsible for the damping or growth rates of the wave amplitudes in the equilibrium and non-equilibrium plasmas. Moving along the stationary magnetic field lines the trapped particles bounce-oscillate between the stop points and are able to interact many times with the wave into the two cyclotron resonance zones, which are symmetric relatively to the plane $z = 0$ in the space between the mirror-points.

Further, the dispersion equation should be solved numerically for the real and imaginary parts of the wave frequency, $\omega = \mathrm{Re}\,\omega + i\,\mathrm{Im}\,\omega$, to define the conditions for the ECW instabilities. As usual, the growth (damping) rate of ECWs, $\mathrm{Im}\,\omega$, is defined by the contribution of the resonant electrons to $\mathrm{Im}\,\chi_{\perp,h}^{n,n}$, that can be readily derived from $\chi_{\perp,\alpha}^{n,n}$ using the well known residue (or Landau rule) method: $\mathrm{Im}\,\chi_{\perp,h}^{n,n} = \sum_{p=1}^{\infty} \mathrm{Im}\,\chi_{\perp,p,h}^{n,n}$, where

$$\mathrm{Im}\,\chi_{\perp,p,h}^{n,n} = \frac{\Omega_{ph}^2 L_0 T_{\parallel h}^2}{\omega\delta\sqrt{\pi} v_{T\parallel h} T_{\perp h}^2} \frac{1}{p^5} \int_0^{\sqrt{\delta}} A_{p,h}^n\left(\kappa, \frac{\varsigma_h}{p}\right) B_{p,h}^n\left(\kappa, \frac{\varsigma_h}{p}\right)$$

$$\times \varsigma_h^4 \exp\left\{-\frac{\varsigma_h^2}{p^2}\left[\kappa^2+(1-\kappa^2)\frac{T_{\parallel h}}{T_{\perp h}}\right]\right\}\kappa(1-\kappa^2)d\kappa \qquad (12)$$

is the separate contribution of bounce-resonant terms to $\mathrm{Im}\,\chi_{\perp,h}^{n,n}$. Here

$$\varsigma_h = \frac{\omega E(\kappa)-\Omega_{c0}K(\kappa)}{\omega_{bh}E(\kappa)}, \qquad (13)$$

so that the wave-particle resonance conditions for energetic h-electrons can be rewritten as $pu=\varsigma_h$, where

$$u = v/v_{T\parallel h}. \qquad (14)$$

In the 1D straight magnetic field case, the transverse dielectric susceptibility tensor component for field-aligned electron-cyclotron waves is

$$\chi_{\perp,\alpha} = \frac{\Omega_{p\alpha}^2}{2\omega^2}\left[\frac{T_{\perp\alpha}}{T_{\parallel\alpha}}-1+\left(\frac{T_{\perp\alpha}}{T_{\parallel\alpha}}-1\right)\frac{\omega-\Omega_{c0}}{k_\parallel v_{T\parallel\alpha}}Z\left(\frac{\omega-\Omega_{c0}}{k_\parallel v_{T\parallel\alpha}}\right)\right.$$
$$\left.+\frac{\omega}{k_\parallel v_{T\parallel\alpha}}Z\left(\frac{\omega-\Omega_{c0}}{k_\parallel v_{T\parallel\alpha}}\right)\right], \qquad (15)$$

where

$$Z(\zeta)=\frac{1}{\sqrt{\pi}}\int_{-\infty}^{\infty}\frac{\exp(-t^2)}{t-\zeta}dt \qquad (16)$$

is the plasma dispersion function.

As a result, the dispersion equation for ECWs in a magnetized plasma confined in the straight uniform magnetic field has the well known form

$$\left(\frac{k_\parallel c}{\omega}\right)^2 = 1+2\sum_{\alpha=c,h}\chi_{\perp,\alpha}, \qquad (17)$$

where the parallel wave number $k_\parallel$ is connected with the eigenmode numbers n as $k_\parallel = n\pi/L_0$. In this case, the squared refractive index of ECWs in a magnetized plasma is defined by the expression

$$\left(\frac{k_\parallel c}{\mathrm{Re}\,\omega}\right)^2 \approx \frac{\Omega_{pe}^2}{\Omega_{c0}(\Omega_{c0}-\mathrm{Re}\,\omega)}, \qquad (18)$$

where $\Omega_{pe}^2 = 4\pi N_e e^2/m_e$ is the squared Langmuir frequency of electrons calculated by the sum-density of the cold (N_c) and hot (N_h) electrons, i.e. $N_e = N_c+N_h$. Analyzing this expression we see that the propagation of ECWs is possible in the frequency range $\mathrm{Re}\,\omega < \Omega_{c0}$.

Another important dispersion characteristic of ECWs is the imaginary part of their frequencies, $\gamma = \mathrm{Im}\,\omega$, characterizing either the temporal growth rate (if $\gamma>0$) or the damping rate (if $\gamma<0$). The increment (decrement) of the ECWs, γ_{1D}, under the condition $\mathrm{Im}\,\omega \ll \mathrm{Re}\,\omega$, is defined by the expression

$$\frac{\gamma_{1D}}{\Omega_{c0}} \approx -2\frac{\mathrm{Re}\,\omega\,(\Omega_{c0}-\mathrm{Re}\,\omega)^2}{\Omega_{pe}^2(2\Omega_{c0}-\mathrm{Re}\,\omega)}\mathrm{Im}\,\chi_{\perp,h}, \qquad (19)$$

where

$$\mathrm{Im}\,\chi_{\perp,h} = \frac{\Omega_{ph}^2\Omega_{c0}\sqrt{\pi}}{2(\mathrm{Re}\,\omega)^2 k_\parallel v_{T\parallel h}}\left[\frac{\mathrm{Re}\,\omega}{\Omega_{c0}}-\left(1-\frac{\mathrm{Re}\,\omega}{\Omega_{c0}}\right)\left(\frac{T_{\perp h}}{T_{\parallel h}}-1\right)\right]$$
$$\times\exp\left[-\left(\frac{\mathrm{Re}\,\omega-\Omega_{c0}}{k_\parallel v_{T\parallel h}}\right)^2\right] \qquad (20)$$

is the contribution of the hot electrons to the transverse susceptibility for the right-hand polarized ECWs. Using these expressions one can demonstrate that the ECW instability is possible if $\mathrm{Im}\,\chi_{\perp,h}<0$. As usual, this is possible if $T_{\perp h} > T_{\parallel h}$.

3. NUMERICAL RESULTS

Now, let us compare the growth rates of ECW instability in the plasmas confined in the 1D straight magnetic field, γ_{1D}, and in the 2D Gas-Dynamic Trap (GDT), γ_{2D}. In our simulations, according to [1], L_0 = 350 cm, H_{0min} = 0.35 T, R_m = 33 cm, a = 14 cm, $N_c = 2\cdot10^{13}\,\mathrm{cm}^{-3}$, $N_h = 0.4\cdot10^{13}\,\mathrm{cm}^{-3}$. The parallel and transverse temperatures of the energetic (resonant) electrons are chosen to be equal to $T_{\parallel h}=10$ keV and $T_{\perp h}=40$ keV, respectively, whereas the temperature of the cold particles is very small and isotropic.

The approximate magnetic field structure in the right half of Gas-Dynamic Trap plasma is shown in Fig. 2. The dashed line shows the magnetic field strength corresponding to the electron-cyclotron resonance at the gyrotron frequency $f = 54.5$ GHz. In this case, the electron-cyclotron resonance condition (ECR zone) is realized at z_{res} = 322 cm. The ECR points, $\pm z_{res}$, are the stop (reflection, mirror) points for the resonant trapped electrons, interacting with the pumping ECW wave by means of the cyclotron and bounce resonances.

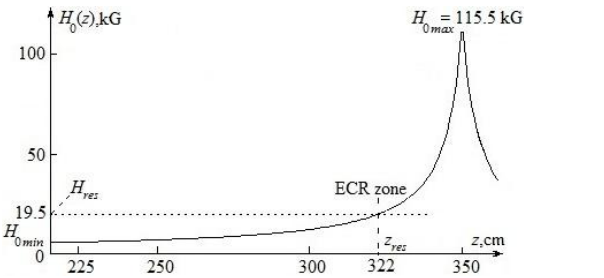

Fig. 2. On-axis distribution of the magnetic field strength $H_0(z)$ in the GDT-like plasma

As a result, the possible longitudinal eigenmode numbers n of ECWs can be estimated by

$$n \approx \frac{L_0\Omega_{pe}\,\mathrm{Re}\,\omega}{\pi c\sqrt{\Omega_{c0}(\Omega_{c0}-\mathrm{Re}\,\omega)}}. \qquad (21)$$

The corresponding dependence $n(\omega)$ is plotted in Fig. 3,a. The ECWs growth rate in the straight magnetic field, γ_{1D}, is shown in Fig. 3,b. For 2D GDT-like plasma the temporal growth rate can be estimated by (12) as

$$\frac{\gamma_{2D}}{\Omega_{c0}} \approx -2\frac{\mathrm{Re}\,\omega\,(\Omega_{c0}-\mathrm{Re}\,\omega)^2}{\Omega_{pe}^2(2\Omega_{c0}-\mathrm{Re}\,\omega)}\mathrm{Im}\,\chi_{\perp,h}^{n,n}. \qquad (22)$$

The dependence of γ_{2D}/Ω_{c0} versus $\omega(=\mathrm{Re}\,\omega)$ for ECW instability is presented in Fig. 3,c for the waves in GDT-like plasma. The computations of γ_{2D} are carried out in the range $2\cdot10^{10}\,\mathrm{Hz} \le \omega \le 4\cdot10^{10}\,\mathrm{Hz}$, whereas the minimal and maximal electron gyrofrequencies are equal to $\Omega_{c0}\approx 6.15\cdot10^{10}$ Hz and $\Omega_{c0max}\approx 2\cdot10^{12}$ Hz, angular gyrotron frequency is $\Omega_f = 2\pi f = 3.42\cdot10^{11}$ Hz.

As it is shown in Fig. 3,b and Fig. 3,c, instability of ECWs is possible for both plasma models in the frequency range $\omega < \Omega_{c0}$ and is impossible if $\Omega_{c0} < \omega < \Omega_{c0max}$.

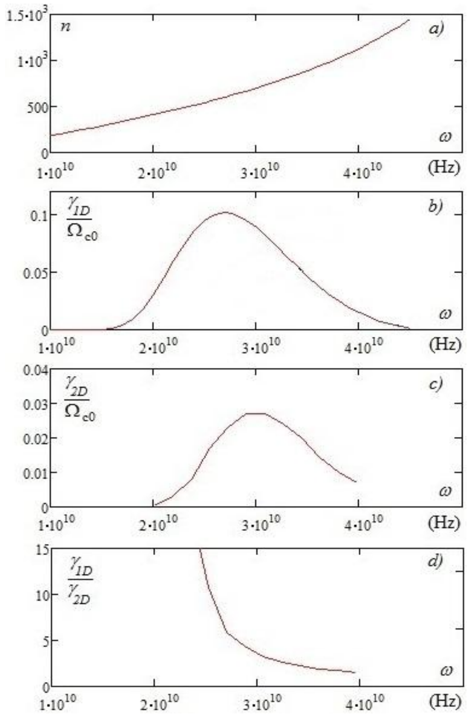

Fig. 3. The dispersion characteristics of ECWs versus ω in a Gas-Dynamic Trap plasma

As one can see, the dependencies γ_{1D} and γ_{2D} on ω are similar (for the same bulk parameters). The ratio $\gamma_{1D}/\gamma_{2D} \propto 2...100$ versus ω for the considered models is presented in Fig. 3,d. This dependence is nonlinear; the difference is very large (by factor 100) for the waves in the low frequency range $\omega \sim 2\cdot10^{10}\,\text{Hz}$ and is smaller (by factor 2) at the high frequencies $\omega \sim 4\cdot10^{10}\,\text{Hz}$.

The large difference between γ_{1D} and γ_{2D} is explained by the fact that the wave-particle interaction in the 1D straight magnetic field plasma is more effective one since the resonant particles move along the uniform magnetic field line with the constant parallel velocity and interact permanently (in time) with the wave. For 2D mirror-trapped plasmas, since $v_\parallel \neq const$ for trapped particles, there is another wave-particle resonance condition involving the particle energy, pitch angle, wave frequency, cyclotron and bounce resonances. As a result, the trapped electrons bouncing between the mirror points only part of the bounce-time can interact effectively with the wave at the ECR zones.

CONCLUSIONS

Let us summarized the main results.

It is shown that ECW instability in a mirror-trapped plasma is possible if $T_{\parallel h} < T_{\perp h}$ only in the range below the minimal electron-cyclotron frequency, that is much less than the pump-frequency (i.e. the gyrotron frequency used for ECR power input into the plasma).

The other feature of electron-cyclotron waves is the fact that their growth rates in 2D mirror-trapped plasmas are much smaller than ones in a 1D cylindrical plasma confined by uniform (straight) magnetic field.

REFERENCES

1. P.A. Bagryansky et al. First results of auxiliary electron cyclotron resonance heating experiment in GDT magnetic mirror // *Nuclear Fusion*. 2014, v. 54(8), p. 082001.
2. N.I. Grishanov, N.A. Azarenkov. Cyclotron wave instabilities in axisymmetric mirror-trapped plasmas with anisotropic temperature // *Plasma Phys. Control. Fusion*. 2009, v. 51, p. 125004.

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ЭЛЕКТРОННО-ЦИКЛОТРОННЫЕ ВОЛНЫ В ЦИЛИНДРИЧЕСКОЙ ПРОБКОТРОННОЙ ПЛАЗМЕ С АНИЗОТРОПНОЙ ТЕМПЕРАТУРОЙ

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Проанализированы дисперсионные характеристики электронно-циклотронных (правополяризованных, необыкновенных) волн в двумерно-неоднородном аксиально-симметричном пробкотроне, содержащем электроны с анизотропной температурой (давлением). Показано, что неустойчивость этих волн возможна лишь в области частот ниже минимальной электронно-циклотронной частоты, то есть при частотах, много меньших гиротронной частоты электромагнитных волн, используемых для ЭЦР-нагрева плазмы, при условии, что поперечная температура резонансных электронов больше их продольной температуры.

ЕЛЕКТРОННО-ЦИКЛОТРОННІ ХВИЛІ В ЦИЛІНДРИЧНІЙ ПРОБКОТРОННІЙ ПЛАЗМІ З АНІЗОТРОПНОЮ ТЕМПЕРАТУРОЮ

М.І. Гришанов, М.О. Азарєнков

Проаналізовано дисперсійні характеристики електронно-циклотронних (правополярізованих, незвичайних) хвиль у двовимірно-неоднорідному аксіально-симетричному пробкотроні, що містить електрони з анізотропною температурою (тиском). Доведено, що нестійкість цих хвиль є можливою лише в діапазоні частот нижче мінімальної електронно-циклотронної частоти, тобто при частотах, багато менших гіротронної частоти електромагнітних хвиль, що використовуються для ЕЦР-нагрівання плазми, за умови, що поперечна температура резонансних електронів є більшою за їхню поздовжню температуру.