ION CYCLOTRON TURBULENCE IN PLASMA OF LOWER HYBRID CAVITIES IN THE EARTH'S IONOSPHERE

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The linear and nonlinear stages of the ion cyclotron instability in plasma of lower hybrid cavities in the Earth's ionosphere are investigated. Because these structures are cylindrically symmetric, the analysis uses the model, which considers as elementary perturbations the small-scale cylindrical waves. It is shown that at the nonlinear stage of instability the suppression of high cyclotron harmonics, as well as short-wavelength part of the spectrum of the azimuthal wave numbers occurs. The estimate of the rate of ion heating is carried out.

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INTRODUCTION

Lower hybrid cavities (LHC) are the common phenomenon in plasma of the topside ionosphere and magnetosphere of the Earth, which were observed in the auroral zone using sounding rockets at altitudes up to 1000 km [1 - 3], as well as satellites from 1000 to 35000 km [4 - 6]. LHC are the spatially localized cylindrically symmetric structures in plasma, whose axis coincides with the direction of the geomagnetic field lines. They are characterized by significantly increased level of electrostatic lower hybrid oscillations, as well as depletion of the plasma density in comparison with the environment. LHC have dimensions across the magnetic field from a few meters to several hundred meters (a few ion Larmor radius) and the dimensions along the magnetic field, considerably exceeding their transverse ones. Apart from the increased level of the lower hybrid oscillations in LHC where also detected the broadband fluctuations in the low frequency range, including the ion cyclotron frequency rang, and which in the background plasma are absent. Here we consider the problem of the occurrence of these oscillations in LHC. We assume that the cause of the ion cyclotron oscillations in the LHC is the inhomogeneity of plasma density in the cavity across the magnetic field and arising as a result of this the drift-cyclotron instability of plasma. Because these structures are cylindrically symmetric, the analysis of both linear and non-linear stages of instability is based on the theory using as elementary perturbations the small-scale cylindrical waves. This theory was developed earlier in papers [7 - 9] for cylindrically symmetric laboratory plasma. We also estimated the rate of heating of the plasma ions in LHC due to ion cyclotron turbulence.

1. LINEAR THEORY

In homogeneous magnetized plasma we consider a cylindrically symmetric cavity whose axis coincides with the direction of the magnetic field. Assume, that the plasma density in the cavity determined by the "inverted" Gaussian distribution

$$n(r) = n_0\left(1 - a\exp\left(-\frac{r^2}{2r_0^2}\right)\right), \qquad (1)$$

where n_0 is the plasma density outside of the cavity; a is a constant determines the depth of the cavity; r_0 is the characteristic length of plasma density inhomogeneity. This dependence of plasma density in the cavity is confirmed by satellite measurements [10]. It was found that $a = 0.1\ldots0.4$ at altitudes of 600…1000 km, $a = 0.1\ldots0.2$, at altitudes of 1500…13000 km, and $a = 0.02\ldots0.05$ at altitudes of 20000…35000 km. Distribution of the components of the plasma velocity assumed Maxwellian, which is also confirmed by observations. The equilibrium distribution function for the components of plasma in this case has the form

$$F_{0\alpha} = \frac{n_0}{(2\pi)^{3/2}\mathrm{v}_{T\alpha}^3}\left(1 - a\exp\left(-\frac{R_\alpha^2}{2R_{0\alpha}^2}\right)\right)\exp\left(-\frac{\rho_\alpha^2}{2\rho_{T\alpha}^2} - \frac{\mathrm{v}_z^2}{2\mathrm{v}_{T\alpha}^2}\right), \qquad (2)$$

where the superscript α denotes ions (i) or electrons (e); R_α, ρ_α and v_z, are the radial coordinate of the guiding center; Larmor radius and velocity along the magnetic field of the particles correspondingly; $R_{0\alpha}$ is the characteristic size of the inhomogeneity of the radial distribution of the guiding centers of particles; $\rho_{T\alpha} = \mathrm{v}_{T\alpha}/\omega_{c\alpha}$ is the thermal Larmor radius; $\mathrm{v}_{T\alpha}$ is the thermal velocity; $\omega_{c\alpha}$ is the cyclotron frequency. Plasma is assumed to slightly inhomogeneous, with $R_{0\alpha} \gg \rho_{T\alpha}$ which also gives $R_{0i} \approx R_{0e} \approx r_0$. Observations have shown that the temperature of ions and electrons in the cavities exceeds the background plasma temperature due to lower hybrid oscillations; it means that the temperatures of the components within the plasma cavity are inhomogeneous and decrease with increasing of radius. Therefore, supposing dependence $\rho_{T\alpha}(R_{0\alpha})$ an arbitrary, we can assume that inequality $\nabla\rho_{T\alpha} < 0$ is met.

For the analysis of ion cyclotron instability in the cavity, we use the dispersion relation describing the linear stage of the small-scale ion cyclotron plasma instability in cylindrically symmetric plasma with arbitrary dependence on the radius of the density and temperature of the plasma components which was obtained in Ref. [9]:

$$\varepsilon(K,\omega,r_s) = 1 + \frac{1}{k^2\lambda_{De}^2}\left[1 + i\sqrt{\pi}\hat{l}_e\frac{\omega W(z_{0e})}{\sqrt{2}k_z\mathrm{v}_{Te}(r_s)}I_0\left(k_\perp^2\rho_{Te}^2\right)\right.$$
$$\left.\times\exp\left(-k_\perp^2\rho_{Te}^2\right)\right] + \frac{1}{k^2\lambda_{Di}^2}\left[1 + i\sqrt{\pi}\sum_{n=-\infty}^{\infty}\hat{l}_i\frac{\omega W(z_{ni})}{\sqrt{2}k_z\mathrm{v}_{Ti}(r_s)}\right.$$
$$\left.\times I_n\left(k_\perp^2\rho_{Ti}^2\right)\exp\left(-k_\perp^2\rho_{Ti}^2\right)\right] = 0\,, \qquad (3)$$

where $z_{n\alpha}=(\omega-n\omega_{c\alpha})/\sqrt{2}k_z \mathrm{v}_{T\alpha}$, $r_s=|m|/k_\perp$, m is the azimuthal wave number, $k_\perp$ and k_z are the wave numbers across and along the magnetic field, $\lambda_{D\alpha}$ is the Debye length, $I_n(x)$ is the modified Bessel function, $W(z)=e^{-z^2}\left(1+\frac{2i}{\sqrt{\pi}}\int_0^z e^{\xi^2}d\xi\right)$, the operator $\hat{l}_\alpha$ is equal to

$$\hat{l}_\alpha=1-\frac{(m+n)\omega_{c\alpha}\rho_{T\alpha}^2}{\omega}\left(\frac{d\ln n_0(r)}{rdr}+\frac{dT_\alpha}{rdr}\frac{d}{dT_\alpha}\right)_{r=r_s}. \quad (4)$$

Equation (3) determines in the small-scale asymptotic limit $k_\perp R_{0\alpha}\gtrsim|m|>1$ the dispersion properties of the spatially inhomogeneous waves structures – cylindrical waves which analytically expressed by Bessel functions $J_m(k_\perp r)$. The dependence of the plasma density (1) as well as temperature on the radial coordinate r in equation (3) is transformed in the depending on the value $r_s=|m|/k_\perp$ that corresponds to the radial coordinate of the first maximum of the Bessel function for which eq. (3) is written, i.e. the coordinate of the point where the oscillating and non-oscillating parts of this function are separated. Assume that the waves propagate almost across the magnetic field, so that $|z_{in}|>1$ and Landau damping by ions can be neglected, however for electrons $|z_{e0}|<1$. Using the corresponding asymptotic forms for the $W(z)$ function, and assuming that the wave numbers $k_\perp$ satisfy the condition $k_\perp\rho_{Ti}>1$, we write the equation (3) for one of the cyclotron harmonic $\omega=n\omega_{ci}+\delta\omega_m(k)$:

$$\varepsilon(K,\omega,R_0)=1+\frac{1}{k^2\lambda_{De}^2}\left(1+i\sqrt{\pi}\frac{\omega-m\omega_{e*}(1-\eta_e/2)}{\sqrt{2}k_z\mathrm{v}_{Te}}\right)$$
$$+\frac{1}{k^2\lambda_{Di}^2}\left(1-\frac{\omega-(m+n)\omega_{i*}(1-\eta_i/2)}{\sqrt{2\pi}k_\perp\rho_{Ti}\delta\omega}\right)=0, \quad (5)$$

where

$$\omega_{\alpha*}=\omega_{c\alpha}\rho_{T\alpha}^2\frac{d\ln n_0(r_s)}{r_s dr_s}\approx\omega_{c\alpha}\frac{\rho_{T\alpha}^2}{r_0^2}ae^{-\frac{r_s^2}{r_0^2}}<<\omega_{c\alpha}$$

is the drift frequency, $\eta_\alpha=d\ln T_\alpha(r)/d\ln n_\alpha(r)$ with $\eta_\alpha<0$. In the dispersion relation (5) as in eq. (3) temperature and density of plasma components are determined at the radius $r_s=|m|/k_\perp$ corresponding to the first maximum of the cylindrical wave $J_m(k_\perp r)$.

The dispersion $\delta\omega_m(k)$ and growth rate obtained from eq. (5) are

$$\delta\omega_m(k)=\frac{n\omega_{ci}}{\sqrt{2\pi}k_\perp\rho_{Ti}}\left(1-\left(1+\frac{m}{n}\right)\frac{\omega_{i*}}{\omega_{ci}}\left(1-\frac{\eta_i}{2}\right)\right), \quad (6)$$

$$\gamma_m(k)\approx\sqrt{\pi}\frac{T_i}{T_e}\frac{n\omega_{ci}}{\sqrt{2}k_z\mathrm{v}_{Te}}\left(\frac{m\omega_{e*}}{n\omega_{ci}}\left(1-\frac{\eta_e}{2}\right)-1\right)\cdot\delta\omega_m(k). \quad (7)$$

The instability occurs due to inverse Landau damping by electrons because of their thermal motion along the magnetic field. We now determine from (6), (7) the range of azimuthal wave numbers for unstable oscillations. Because in the cavity $\nabla n_0(r)>0$, then the drift frequencies satisfy the inequalities $\omega_{e*}<0$ and $\omega_{i*}>0$. In this case, the growth rate is positive and instability occurs when the azimuthal wave number satisfies the inequality

$$m<-m_{01}=-\frac{n\omega_{ci}}{|\omega_{e*}|(1-\eta_e/2)}<0. \quad (8)$$

Obviously, for weakly inhomogeneous plasma the inequality

$$m_{01}\approx n\frac{T_i}{T_e}\frac{r_0^2}{a\rho_{Ti}^2(1-\eta_e/2)}e^{\frac{r_s^2}{r_0^2}}>>1 \quad (9)$$

holds and the applicability of small-scale approximation is provided. In addition, we verify the validity for the assumption $k_\perp\rho_{Ti}>1$:

$$k_\perp\rho_{Ti}=k_\perp r_0\frac{\rho_{Ti}}{r_0}\approx m_{01}\frac{\rho_{Ti}}{r_0}\approx\frac{T_i}{T_e}\frac{r_0}{a\rho_{Ti}(1-\eta_e/2)}e^{\frac{r_s^2}{r_0^2}}>1. \quad (10)$$

The last inequality for the parameters of LHC holds. Note that the scale of oscillations depends not only on the ratio r_0/ρ_{Ti} but on the depth of the cavity a. Wavelengths are smaller, the smaller the depth of the cavity.

2. NONLINEAR THEORY

Nonlinear evolution of ion cyclotron instability at the first stage is determined by the induced scattering of cylindrical waves by ions. The equation for the spectral intensity $I_m(k)$ of cylindrical waves describes this process for the ion cyclotron instability has the form [9]:

$$\frac{1}{2}\frac{\partial I_m(k)}{\partial t}=(\gamma_m(k)+\Gamma_m(k))I_m(k), \quad (11)$$

where $\Gamma_m(k)$ is the nonlinear decrement:

$$\Gamma_m(k)=\left(\frac{\partial\,\mathrm{Re}\,\varepsilon}{\partial\omega_m(k)}\right)^{-1}\sum_{m_1}\int dk_1 I_{m_1}(k_1)B(k_\perp,m|k_{1\perp},m_1)$$
$$\times\,\mathrm{Im}U_i\left(k,m,\omega_m(k)|k_1,m_1\omega_{m_1}(k_1)\right). \quad (12)$$

Here ε is given by eq. (5), $B(k_\perp,m|k_{1\perp},m_1)$ is the coefficient of nonlinear interaction of cylindrical waves [7, 8]:

$$B(k_\perp,m|k_{1\perp},m_1)=\begin{cases}\frac{1}{\pi m|\cos\alpha_0|}\frac{k_\perp}{k_{1\perp}}, & m_1<m_{10}-m_{10}^{1/3}\\ O(m^{-2/3}), & m_{10}-m_{10}^{1/3}<m_1<m_{10}\\ O(m^{-2}), & m_1>m_{10},\end{cases} \quad (13)$$

where $m_{10}=mk_{1\perp}/k_\perp$, $\cos^2\alpha_0=1-r_{1s}^2/r_s^2$, $r_{1s}=|m_1|/k_{1\perp}$; $\mathrm{Im}U_i$ is the matrix element of induced scattering of waves by ions equals

$$\mathrm{Im}U_i\approx-\frac{1}{k^2\lambda_{Di}^2}\frac{e^2}{T_i^2}k_\perp k_{1\perp}\rho_{Ti}^2\left(\cos^2\alpha_0\ln k_\perp\rho_{Ti}+O(1)\right)$$

$$\times \sum_{n_1} \frac{\omega_{ci}^3}{(\delta\omega)^2} \left[(n-n_1) - (m-m_1) \frac{\omega_{i2}^*}{\omega_{ci}} \left(1 - \frac{\eta_i}{2} \right) \right]$$
$$\times \delta(\delta\omega - \delta\omega_1), \tag{14}$$
where $\omega_{i2}^* = -\omega_{ci}\rho_{Ti}^2 (d \ln n_0(r)/rdr)_{|r=r_{2s}}$, $r_{2s} = |m_2|/k_{\perp 2}$. Value r_{2s} is equal to the radial coordinate of the first maximum of the cylindrical beat wave for the waves $J_m(k_\perp r)$ and $J_{m_1}(k_{1\perp} r)$. The beat wave has the wave numbers determined by

$$m_2 = m - m_1,\ k_{2\perp}^2 = k_\perp^2 + k_{1\perp}^2 - 2k_\perp k_{1\perp} \cos\left(\frac{\pi}{2} - \alpha_0\right);$$
$$= k_\perp^2 + k_{1\perp}^2 - 2k_\perp^2 \frac{m_1}{m}. \tag{15}$$

Induced scattering of cylindrical waves has characteristic distinction from a similar process of plane waves. In the case of plane waves to obtain the equation describing the nonlinear evolution of the spectral intensity $I(\mathbf{k_1})$ of the wave-interaction partners, it is sufficient to replace

$$\mathbf{k} \rightleftarrows \mathbf{k_1},\ \omega(\mathbf{k}) \rightleftarrows \omega_1(\mathbf{k}_1) \tag{16}$$

and take into account the basic properties of the symmetry of the matrix elements. In this case the appearance of non-linear increment in the equation for the spectral intensity $I(\mathbf{k})$ is accompanied by the appearance of symmetric nonlinear decrement in the equation for $I(\mathbf{k_1})$ and vice versa. In the case of cylindrical short-waves in the derivation of equation for $I_{m_1}(k_1)$ in addition to replacements (16) should also take into account the relation (13) as well as inequality $\cos^2\alpha_0 < 1$ or $r_{1s} < r_s$. Their accounting leads to an asymmetric response influence of wave $J_m(k_\perp r)$ to wave $J_{m_1}(k_{1\perp} r)$, which reduce the nonlinear decrement in the equation for $I_{m_1}(k_1)$ in $|m| >> 1$ times. Thus, the process of induced scattering of short cylindrical waves is asymmetric. This asymmetry of the nonlinear interaction of cylindrical waves leads to the appearance of forbidden and permitted intervals of azimuthal wave numbers m_1 affecting on the wave with azimuthal wave number m, that significantly affects on the evolution of instability.

Now we consider the effect of induced scattering of cylindrical waves on the ion cyclotron instability with the parameters of LHC, when conditions $\nabla n_0 > 0$, $\eta_e < 0$, $\eta_i < 0$ are met. Proportionality of the matrix element (14) to δ-function determines the transverse wave numbers of the interacting cylindrical waves: $n/k_\perp \approx n_1/k_{1\perp}$. In its turn the requirement $r_{1s} < r_s$ determines the limit on the azimuthal wave numbers m_1: $|m_1|/n_1 < |m|/n$. Taking into account the inequality (8) we obtain permitted interval for these wave numbers:

$$\frac{mn_1}{n} < m_1 < -m_{01} < 0. \tag{17}$$

For azimuthal wave numbers determined by (9) and (17) the first term in the square brackets of eq. (14) is greater than the second one in T_e/T_i times and at the first phase of the nonlinear evolution of the oscillation spectrum the main process is the interaction of different cyclotron harmonics with $n\omega_{ci} \neq n_1\omega_{ci}$. As a result at the energy density fluctuations $W \approx n_0 T_i (T_i/T_e)(k_\perp \rho_{Ti})^{-4}$ the high-frequency part of the spectrum of the drift-cyclotron instability is suppressed; so that only main cyclotron harmonic with $n = 1$ remains (see also [11]).

At the second phase of the nonlinear evolution of spectrum, when the first term in the square brackets vanishes, a nonlinear interaction of waves with different values of the azimuthal wave numbers becomes the main. Taking into account inequality $m < m_1 < 0$ we obtain for nonlinear decrement $\Gamma_m(k) \propto \sum_{m_1<m} (m - m_1) < 0$. This leads to damping of shorter wave $J_m(k_\perp r)$ compared with $J_{m_1}(k_{1\perp} r)$ wave, and ultimately to the suppression of the short-wavelength part of the azimuthal wave numbers spectrum. As a result the narrow part of the spectrum near the boundary value $m = -m_{01}$ (9) remains. Simultaneously the evolution of the spectrum of the transverse wave numbers $k_\perp$ does not occur so that the frequency spectrum near the fundamental harmonic of the ion cyclotron frequency, which is determined by the dispersion (6), does not change.

The second stage of the evolution of the drift-cyclotron instability is determined by the scattering of particles in the random fluctuations of the electric field drift-cyclotron turbulence (broadening of the resonance) [12, 13]. At this phase the saturation of growing fluctuations at the level [8]:

$$\frac{W}{n_0 T_i} \approx \frac{1}{(k_\perp \rho_{Ti})^4} \approx \left(\frac{T_e}{T_i} \frac{a\rho_{Ti}}{r_0} \right)^4. \tag{18}$$

The ion cyclotron turbulence in the LHC leads to additional turbulent heating of the plasma ions. To determine the rate of heating we use the results of [14], where was estimated the rate of quasi-linear change of the thermal Larmor radius, resulting from collisions with turbulent fluctuations of the electrostatic fields:

$$\frac{\partial \bar{\rho}_i}{\partial t} \sim \mathrm{v}_{Ti} \frac{T_i}{T_e} \frac{1}{(k_\perp \rho_{Ti})^5} \sim \mathrm{v}_{Ti} \frac{T_i}{T_e} \left(\frac{T_e}{T_i} \frac{a\rho_{Ti}}{r_0} \right)^5. \tag{19}$$

Characteristic time of variation of the thermal Larmor radius due to ion cyclotron turbulence is of the order of

$$\tau_\rho \sim \frac{1}{\omega_{ci}} \frac{T_i}{T_e} \left(\frac{T_e}{T_i} \frac{a\rho_{Ti}}{R_0} \right)^5. \tag{20}$$

The rate of heating of the ions due to ion cyclotron turbulence is much less than the ion cyclotron frequency, and therefore the contribution of the ion cyclotron heating compared with the lower-hybrid heating is insignificant.

CONCLUSIONS

In plasma of the lower hybrid cavities which exist in the Earth's topside ionosphere and magnetosphere, the ion cyclotron instability may occurs due to the radial inhomogeneity of plasma. For weakly inhomogeneous plasma in cavities as well as for cavities with small depth, the cylindrical waves are short across the magnetic field; the azimuthal and transverse wave numbers are given by the expressions (9) and (10).

At the nonlinear stage of development of instability the higher cyclotron harmonics in the frequency spectrum as well as the short-wavelength part of the spectrum of the azimuthal wave numbers are suppressed due to induced scattering of waves by ions. As a result only first harmonic of the ion cyclotron oscillations and a narrow part of the spectrum near the long-wavelength stability boundary (9) remain in the spectrum. The instability saturates at energy density fluctuations (18) due to the effect of scattering of ions by the random fluctuations of the electric fields of drift-cyclotron turbulence. The development of the instability is accompanied by turbulent heating of the ions; however, the contribution of this effect compared with the lower hybrid heating is insignificant.

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ИОННАЯ ЦИКЛОТРОННАЯ ТУРБУЛЕНТНОСТЬ ПЛАЗМЫ НИЖНЕГИБРИДНЫХ ПОЛОСТЕЙ ЗЕМНОЙ ИОНОСФЕРЫ

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Исследуются линейная и нелинейная стадии ионной циклотронной неустойчивости в плазме нижнегибридных полостей земной ионосферы. Поскольку такие структуры имеют цилиндрическую симметрию, анализ проводится на основе модели, рассматривающей в качестве элементарных возмущений мелкомасштабные цилиндрические волны. Показано, что на нелинейной стадии неустойчивости происходят подавления высоких циклотронных гармоник, а также коротковолновой части спектра азимутальных волновых чисел. Выполнена оценка скорости нагрева ионов.

ІОННА ЦИКЛОТРОННА ТУРБУЛЕНТНІСТЬ ПЛАЗМИ НИЖНЬОГІБРИДНИХ ПОРОЖНИН ЗЕМНОЇ ІОНОСФЕРИ

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Досліджуються лінійна та нелінійна стадії іонної циклотронної нестійкості в плазмі нижньогібридних порожнин земної іоносфери. Оскільки такі структури мають циліндричну симетрію, аналіз проводиться на основі моделі, що розглядає в якості елементарних збурень дрібномасштабні циліндричні хвилі. Показано, що на нелінійній стадії нестійкості відбуваються пригнічення високих циклотронних гармонік, а також короткохвильової частини спектра азимутальних хвильових чисел. Виконано оцінку швидкості нагріву іонів.