INFLUENCE OF THE ION TEMPERATURE ANISOTROPY ON THE RELAXATION PROCESSES IN A MAGNETIZED PLASMA

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The processes of temperature relaxation under conditions of the parametric excitation of an ion-cyclotron wave by the lower-hybrid (LH) pump in a magnetized plasma with the ion temperature anisotropy have been considered. The inverse relaxation time in the region above the instability threshold has been calculated, as well as its dependences on the amplitude of the electromagnetic field and the ion temperature anisotropy. The results derived are useful for plasma diagnostics.

The problem of equilization of the electron and ion temperatures in an isotropic plasma in the absence of external fields was considered in [1]. The temperature relaxation in a magnetized plasma was dealt with in [2], where the relaxation rate of the difference between the ion and electron temperatures was found to include, in addition to a conventional "Spitzer's" term, the terms with a logarithmic divergence of the type $\ln(m_e/m_i)$. The influence of an external electromagnetic irradiation on the temperature relaxation in an isotropic plasma was studied in [3]. The high-frequency electric field was shown to increase the relaxation time.

The authors of work [4] demonstrated that the high-frequency electric field with a frequency close to that of the LH resonance affects substantially the relaxation rate between the ion and electron temperatures in a magnetized uniform plasma. An extra term caused by the pump field has been revealed in the inverse relaxation time. This term anomalously grows when the amplitude of the pump field approaches the threshold value of the electric field.

The relaxation between the electron and ion temperatures in a magnetized nonuniform plasma in the case of the parametric decay of a pump wave into the LH and electron-drift ones was considered in [5] in the framework of the kinetic theory of fluctuations. The inverse relaxation time and its dependence on the plasma density gradient and the pump wave intensity were determined in the region beyond the threshold of a parametric instability. The presence of the parametric instability was shown to result in a reduction of the relaxation time.

In this work, the relaxation process between the ion and electron temperatures was considered under the conditions where the parametric excitation of a ion-cyclotron wave by the LH pump in a magnetized plasma with the ion temperature anisotropy takes place. The inverse relaxation time in the turbulent fluctuation mode was calculated, and its dependences on the ion temperature anisotropy and the electric field amplitude were obtained.

Consider an electron-ion magnetized plasma when exposed to a high-frequency (HF) pump field, the frequency of which, ω_0, is close to that of the LH resonance, i.e. $\omega_0 \sim \omega_{\rm LH} = \omega_{pi}\left(1+\omega_{pe}^2/\Omega_e^2\right)^{-1/2}$, where $\omega_{p\alpha}$ is the plasma frequency of particles of the kind α, $\Omega_\alpha = e_\alpha B_0/m_\alpha c$ is the cyclotron frequency, and B_0 is an external magnetic field directed along the OZ-axis. The field of the pump wave is chosen in the dipole approximation as $\mathbf{E}(t) = \{0, E_0, 0\}\cos\omega_0 t$.

Let us express the relaxation time between the ion and electron temperatures through the energy density absorbed in a time unit

$$W_i = \frac{3}{2} n_e \dot{T}_e, \tag{1}$$

where n_α and T_α are the concentration and the temperature, respectively, of particles of the α-th kind.

On the other hand, we have

$$\dot{T}_e = -\frac{T_e - T_i}{\tau_{ei}} \approx -\frac{T_e}{\tau_{ei}} \approx -\frac{T_e}{\tau_{ei}}. \quad (2)$$

While comparing relations (1) and (2), we get

$$\frac{1}{\tau_{ei}} = -\frac{W_i}{\frac{3}{2} n_e T_e}, \quad (3)$$

where the power density of the HF-energy which is absorbed by ions is connected to the collision integral $I(\mathbf{p})$ through the expression [7]

$$W_i = n_i \int \frac{p^2}{2m_i} I(\mathbf{p})\, d\mathbf{p}. \quad (4)$$

As has been shown in [8], the action of an LH pump wave in the plasma system described above can result in the appearance of various parametric instabilities. We will study the parametric interaction of the LH wave with the harmonics of the ion-cyclotron frequency ($\omega \approx n\Omega_i$). The frequency and the damping parameter of such oscillations for the case $n = 1$ are determined by the known relations [9, 10]

$$\mathrm{Re}\omega \equiv \omega^{(1)} = \Omega_i [1 + A_1(\beta_{\perp i})], \quad (5)$$

$$\mathrm{Im}\omega \approx \gamma_i^{(1)} = \left(\frac{\pi}{2}\right)^{\frac{1}{2}} \frac{A_1^3 \Omega_i^2}{k_{||} v_{||i}} \frac{T_{\perp i}}{T_{||i}} \exp\left(-\frac{A_1^2 \Omega_i^2}{2k_{||}^2 v_{||i}^2}\right). \quad (6)$$

In Eqs. (5) and (6), $A_n(\beta_{\perp i}) = I_n(\beta_{\perp i}) e^{-\beta_{\perp i}}$, where I_n is the modified Bessel function, $\beta_{\perp i} \approx (k\rho_{\perp i})^2 > 1$. Moreover, Eqs. (5) and (6) were obtained at $v_{||i} \ll \omega/k_Z \ll v_{||e}$ for the case which is interesting in applications, namely, when $T_{||i}/T_{\perp i} < A_1 \ll 1$.

We should emphasize that such ion-cyclotron oscillations may propagate in a plasma with an anisotropic distribution of the ion velocities, when the unperturbed distribution function has the form

$$f_{0\alpha} \sim \left(\frac{T_{\perp i}}{T_{||i}}\right) \exp\left(-\frac{m_i v_{\perp i}^2}{2T_{\perp i}} - \frac{m_i v_{||i}^2}{2T_{||i}}\right).$$

Note that the anisotropic distribution of the ions over velocities is typical of the plasma held in adiabatic traps. In this case, all the ion anisotropic instabilities possess the frequencies close to the ion-cyclotron one and its harmonics, with the increments and the conditions for the emergence of those instabilities essentially depending on a degree of ion anisotropy.

Let the decay conditions

$$\omega_0 = \omega_{\mathrm{LH}} + \omega^{(1)} \quad (7)$$

be fulfilled, where ω_{LH} is the LH frequency, and $\omega^{(1)}$ is determined by formula (5).

Consider the turbulent plasma mode, when the amplitude of the pump wave exceeds the field threshold value [10]

$$E_{\mathrm{thr}}^2 = \frac{p}{T_{||i}} \left(\frac{T_{\perp i}}{T_{||i}}\right)^{1/2} \exp\left(-\frac{q}{T_{||i} T_{\perp i}}\right), \quad (8)$$

where the coefficients p and q are determined by the expressions

$$p = 4\frac{\omega_0^2 B_0^2 r_{De}^2}{k^2 c^2 \cos\vartheta} \frac{\gamma_{LH}}{\omega_{LH}} m_i \Omega_i^2, \quad q = \frac{\Omega_i^4 m_i^2}{4\pi k^4 \cos^2\vartheta}.$$

Under those conditions, the fluctuations of the electric field intensively develop, considerably exceeding the level of thermal noises. As a result, the diffusion coefficient in the velocity space grows substantially and gives the main contribution to the collision integral (as compared to the coefficient of the dynamic friction). Then, the power density of the HF energy, which is absorbed by plasma ions, can be written as [7]

$$W_i = \int \frac{d\mathbf{k}}{(2\pi)^3} \int \frac{d\omega}{2\pi} \frac{\langle \delta\mathbf{E}\delta\mathbf{E}\rangle_{\omega,\mathbf{k}}}{4\pi} \omega\, \mathrm{Im}\chi_i^0, \quad (9)$$

where the spectral density of turbulent fluctuations of the electric field $\langle \delta\mathbf{E}\delta\mathbf{E}\rangle_{\omega,\mathbf{k}}$ in the region beyond the threshold of parametric instability can be obtained from the expression found earlier [4], in which the own plasma frequencies ω_j should be replaced by $\omega_j + i\gamma_{\mathrm{turb}}$ ($\omega_j = \omega_{\mathrm{LH}}$ for the LH wave and $\omega^{(1)}$ for the ion-cyclotron one). Here, we introduced the turbulent frequency of collisions γ_{turb} which characterizes an additional wave damping on the turbulent fluctuations of a plasma and defines the HF-energy power of the pump wave absorbed in the plasma. The physical essence of this mechanism consists in the expansion of the group of resonant particles interacting with waves, which leads to the stabilization of a parametric instability.

Substituting the redefined value of the correlator into Eq. (9) and integrating over ω and $\mathbf{k}$, we get the formula for the density of the HF-energy power absorbed by the ionic component of the plasma

$$W_i \approx \frac{1}{2} \frac{e^2 n_e E_0^3}{m_e \omega_0^2 E_{\mathrm{thr}}(k_0)} \left[\gamma_i^{(1)}(k_0)\, \gamma_{LH}(k_0)\right]^{1/2}, \quad (10)$$

where k_0 is the wave number to be determined from the decay conditions as

$$k_0 = \frac{\Omega_i}{(2\pi)^{1/2} \rho_{\perp i} (\omega_0 - \omega_{\mathrm{LH}} - \Omega i)}.$$

Note that we left a single term, which makes the main contribution into (9), in Eq. (10). Substituting expression (10) into formula (3), we obtain ultimately

$$\frac{1}{\tau_{ei}} \approx \frac{1}{3}\frac{e^2 E_0^3}{m_e \omega_0^2 T_e E_{\rm thr}} \left(\gamma_i^{(1)} \gamma_{\rm LH}\right)^{1/2}. \quad (11)$$

As is seen from Eq. (11), the relaxation rate of the ion and electron temperatures depends rather strongly on the amplitude of the electric field ($\tau_{ei}^{-1} \sim E_0^3$). Taking into account Eq.(6), it is not difficult to determine also the dependence of the inverse relaxation time on the ionic temperature anisotropy:

$$\frac{1}{\tau_{ei}} \sim \left(\frac{T_{\perp i}}{T_{||i}}\right)^{1/4} \exp\left(\frac{q}{2T_{\perp i}^2}\frac{T_{\perp i}}{T_{||i}}\right). \quad (12)$$

Thus, varying the relation between the ionic temperatures $T_{\perp i}$ and $T_{\| i}$, it is possible to increase or decrease the relaxation time of the ion and electron temperatures and, hence, to influence the rate of the plasma HF-heating.

In the authors' opinion, the results of the present work are interesting both from the viewpoint of the further research of fundamental properties of the parametrically unstable magnetized plasma and for the needs of plasma diagnostics.

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ВПЛИВ АНІЗОТРОПІЇ ІОННОЇ ТЕМПЕРАТУРИ
НА ПРОЦЕСИ РЕЛАКСАЦІЇ В ЗАМАГНІЧЕНІЙ ПЛАЗМІ

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Р е з ю м е

Розглянуто процеси релаксації температур в умовах, коли відбувається параметричне збудження іонно-циклотронної хвилі нижньогібрідною (НГ) накачкою в замагніченій плазмі з анізотропією іонної температури. Обчислено обернений час релаксації в запороговій області параметричної нестійкості і його залежність від амплітуди електричного поля та анізотропії іонної температури. Результати цієї роботи є цікавими для плазмової діагностики.