ION-SOUND PARAMETRIC TURBULENCE OF PLASMA IN MAGNETIC FIELD

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It is shown that excitation of ion-sound turbulence and related electron turbulent heating in the fields of ion-sound turbulence may be the main process of helicon energy absorption in the helicon plasma sources.

The action of the strong electromagnetic wave on plasma results in the relative oscillatory motion of plasma components, which is the source of the numerous parametric instabilities In the strongly non-isothermal plasma with hot electrons and cold ions the excitation of the ion-sound parametric kinetic instability is possible [1]. The nature of the ion-sound parametric kinetic instability is analogous to one of the ion-sound plasma instability with transverse current [2]. The difference between these instabilities is essentially in the different manifestation of the Doppler effect in the case of the inertial and oscillatory (non-inertial) frames of reference: an elementary sine disturbance in the laboratory frame of reference is recognised in the oscillating frame connected with the electron component as a set of beats formed by plasma oscillations and harmonics of the pumping wave. For short wave $k_{\perp}\rho_e >> 1$ ion-sound perturbations the frequency $\omega\left(\vec{k}\right)$ and growth rate $\gamma\left(\vec{k}\right)$ are (see also [1])

$$\omega\left(\vec{k}\right) = \frac{kv_s}{\left(1+k^2 r_{De}^2\right)^{1/2}} \equiv \omega_s\left(\vec{k}\right)$$

$$\gamma(k) = \gamma_e(k) = -\frac{\omega_s(k)}{2\sqrt{2}k_{\perp}\rho_e\left(1+k^2 r_{De}^2\right)} \sum_{p=-\infty}^{\infty} J_p^2(a) z_{e0}^{(p)}\, exp\left(-\left(z_{e0}^{(p)}\right)^2\right) \qquad (1)$$

where $z_{e0}^{(p)} = \dfrac{\omega_s(k) - p\omega_0}{\sqrt{2}\left|k_{||} - pk_{0||}\right| v_{Te}}$, $a = a_e \approx \dfrac{c}{\omega_0 B_0}\left(k_x^2 E_{oy}^2 + k_y^2 E_{ox}^2\right)^{1/2}$. It results from (1) that the waves for which $\omega_s(k) < p\omega_0$ are unstable. In the case of strong ellipticity of the pumping wave, for example when $E_{0x} >> E_{0y}$, the strongly anisotropic wave spectrum with $k_x >> k_y$ is excited,

$$k_y \left| \frac{E_{0x}}{E_{0y}} \right| \geq k_x \sim \frac{\omega_0}{v_s} >> k_y \sim \frac{\omega_0}{u} a \qquad (2)$$

For those waves the greatest contribution in p-sum in (1) is made by the term with p=1, which is at maximum at $a \approx 1.8 - 2.2$ and the contribution in γ_e of other terms with $p \neq 1$ are found to be small and γ_e is equal to

$$\gamma_e \cong 0.05\sqrt{\omega_{ce}\omega_{ci}} \cdot \left(1 + k^2 r_{De}^2\right)^{-3/2} \qquad (3)$$

The conditions (2) are satisfied for $u \cong cE_{0x} / B_0 >> av_s$. In the equation (1) we suppose the ions to be unmagnetized $\left(2\pi\gamma_e >> \omega_{ci}, k\rho_i >> 1\right)$. The equation (1) we have obtained without accounting for the ion Landau damping of the ion-sound wave γ_i as well as for the collisional damping due to the ion viscosity γ_v. When we take into account these effects, the growth rate will be determined by the equation $\gamma = \gamma_e - \gamma_i - \gamma_v$, . The accounting of terms with γ_v and γ_i leads to the restriction of the possible values of T_i and T_e , for which the excitation of the ion-sound kinetic parametric instability is possible.

The main weak-nonlinear process which may result in the saturation of the instability considered is the induced scattering of the ion-sound waves on ions. This process is governed by the equation for the ion-sound waves spectral intensity $I\left(\vec{k}, t\right)$,

$$\left(1/2\right)\partial I / \partial t = \left(\gamma + \Gamma\right) I\left(\vec{k}, t\right),$$

where nonlinear damping rate Γ was determined in [3]. The saturation occurs with the waves energy density W , where $\gamma + \Gamma = 0$ To the order of magnitude it is equal to

$$\frac{W}{n_{oe}T_e} \sim \frac{T_e}{T_i} \frac{\gamma}{\pi k v_s} \qquad (4)$$

The electron heating rate is found from the quasilinear equation for the averaged electrons distribution function F_{e0},

$$\frac{\partial F_{e0}}{\partial t} = \pi \frac{e^2}{m_e^2} \sum_{p=-\infty}^{\infty} \int d\vec{k} J_p^2(a) k_{||}^2 I\left(\vec{k}\right) J_0^2\left(\frac{k_\perp v_{e\perp}}{\omega_{ce}}\right) \frac{\partial}{\partial v_{e||}} \left(\delta\left(\omega(k) - p\omega_0 - k_{||}v_{e||} - pk_{o||}v_{e||}\right) \frac{\partial F_{e0}}{\partial v_{e||}}\right) \qquad (5)$$

where $\vec{v}_e$ is the electron velocity in the electron oscillating frame of reference. Multiplying (5) by $m_e v_{e\|}^2 / 2$ and integrating over the velocities one obtains that

$$n_{0e} \frac{dT_{e||}}{dt} = \sum_{p=-\infty}^{\infty} \int d\vec{k} W\left(\vec{k}\right) \frac{p\omega_0 - \omega\left(\vec{k}\right)}{\omega\left(\vec{k}\right)} \gamma_{pe}\left(\vec{k}\right) \quad = \frac{n_{0e}T_{e||}}{\tau_h}$$

where $\gamma_{pe}(k) = -\left(\frac{\partial\varepsilon_i}{\partial\omega(k)}\right)^{-1} J_p^2(a)\, Im\,\delta\varepsilon_e\left(\vec{k} - p\vec{k}_0, \omega(\vec{k}) - p\omega_0\right)$

The time scale τ_h of the electron temperature growth due to Cherenkov interaction of electrons with ion-sound waves at their saturation state (4) can be estimated as

$$\frac{1}{\tau_h} \sim \gamma_e \frac{W}{n_0 T_e} \sim \frac{\gamma\gamma_e}{\pi k v_s}. \qquad (6)$$

The helicon damping due to the excitation of ion-sound turbulence and turbulent electrons heating are estimated via the effective frequency of electron scattering on ion-sound oscillations, which we obtain from the energy balance equation

$$2\nu_{eff} \frac{k_0^2 c^2}{\omega_{pe}^2} W_0 \approx n_{0e} \frac{dT_{e||}}{dt} = \frac{n_{0e} T_{e||}}{\tau_h}. \qquad (7)$$

Here $\vec{k}_0$ and W_0 are the helicon wave number and helicon energy density, respectively,

$$k_0 = \frac{\omega_{pe}^2 \omega_0}{\omega_{ce} c^2 k_{0||}}, \qquad k_{0||} \| B_0,\; W_0 \approx \frac{1}{16\pi} \left|\tilde{B}\right|^2 \approx \frac{m_e n_{0e} u^2}{2} \frac{\omega_{ce}}{\omega_0} \frac{k_{0||}}{k_0},$$

$\tilde{B}$ is the helicon magnetic field strength $, u = cE_0 / B_0$. Accounting for (4), (5) we estimate ν_{eff} as

$$\nu_{eff} \sim \gamma_e \frac{W}{2W_0} \frac{\omega_{ce}}{\omega_0} \frac{k_{0||}}{k_0} \sim \gamma \frac{T_e}{2\pi T_i} \frac{\gamma}{\omega_s} \frac{v_{Te}^2}{u^2} \qquad (8)$$

The experimental conditions of ref.[4] are: $B_0 = 800G$, $\tilde{B}_z = 4G$, $n_e = 10^{13}\, cm^{-3}$ $T_e = 4eV$ Plasma is produced with the 1-2 kW power generator of frequency $\omega_0 = 1.7 \cdot 10^8 s^{-1}$. The maximum magnitude of the helicon magnetic field, $\tilde{B}_z \approx 7G$, was observed at the radius r = 1cm near the antenna edge and decrease to $\tilde{B}_z \approx 4G$ at the distance $\Delta z = 15cm$ from antenna and to $\tilde{B}_z = 3G$ at $\Delta z = 45cm$=45cm. The longitudinal, $k_{0\|}$, and transversal $k_{0\perp}$, helicon wave numbers are $k_{0||} \sim \pi / L_{||} \sim 0.3 cm^{-1}, k_{0r} \sim 1.6 cm^{-1}$. In that case the components of the helicon electrical field strength are

$$E_{0r} = E_{0x} \approx 24V / cm, E_{0\varphi} \approx E_{0y} = 6V / cm, E_{0z} \approx 3 \cdot 10^{-2} V / cm..$$

Under these conditions the excitation of the short-wave ion-sound parametric instability with parameters

$$k_x \sim \omega_s / v_s \sim 400 cm^{-1}, \quad k_y \sim 1.8\omega_0 / u \sim 50 cm^{-1} (a_e = 2.2), \; k_{||} \sim 0.6 cm^{-1}$$

$$\omega_s \sim 0.7\omega_0 = 1.2 \cdot 10^8 s^{-1}$$

becomes possible. In experiment [4], T_i is unknown. We assume $T_e / T_i = 20 (T_i = 2200^\circ K)$ and obtain $\gamma_v = 1.6 \cdot 10^5 s^{-1}, \gamma_i = 3.0 \cdot 10^5 s^{-1}$ and growth rate $\gamma = \gamma_e - \gamma_i - \gamma_v = 1.84 \cdot 10^6 s^{-1}$, and $\gamma_e = 2.3 \cdot 10^6 s^{-1}$. We we obtain that $W \sim 0.1 n_{oe} T_e \quad (T_e = 4eV)$, the time of the turbulent electrons heating $\tau_h = 3.3 \cdot 10^{-6} s$, and $\gamma\tau_h = 6$, For this case $\nu_{eff} \sim 7.5 \cdot 10^8 s^{-1}$. Note that the electron-ion collision frequency ν_{ei} for is equal to $\nu_{ei} = 3.8 \cdot 10^7 s^{-1}$ which is less than corresponding values of ν_{eff}.

The helicon damping length along the magnetic field due to the generation of the ion-sound turbulence is equal to $l_t \sim \omega / k_0 \nu_{eff}$ For the experimental conditions of Ref. [4] we obtain $l_t \leq 11 cm$ at $T_e = 4eV$ which is in agreement with the measurements of Ref. [4]. The collisional damping length $l_c \sim \omega_{ce} / \nu_{ei} k_0$ is found to be $l_c \sim 2.2 m$ for $T_e = 4eV$. Thus the turbulent helicon damping is more than an order of magnitude stronger than the collisional one. This damping helps to understand the nature of the helicon source operation in which the discharge sustainment and plasma heating are due to the ion-sound parametric turbulence. From the said above we can give the interpretation of the temperature profile calculations in the downstream region . The temperature profile at the distances $\Delta z \geq 20 cm$ from the antenna edge is due only to collisional thermoconductivity and elastic and inelastic collisions. The initial (injected) heat flax is due to the anomalous turbulent heating in the near-antenna region, because at the distances from the antenna edge exceeding 25 cm the electron temperature T_e becomes equal or less than 3 eV and at $T_i = 0.2 eV$ the ion-sound turbulence is quenched due to strong Landau absorption by ions.

References

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