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TRANSFORMATION PROCESSES IN STRONGLY MAGNETIZED TURBULENT PLASMA WITH UPPER HYBRID PUMP

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On the base of kinetic theory fluctuations the transformation of transverse electromagnetic wave into a longitudinal Langmuir wave is investigated in strongly magnetized uniform plasma when the plasma turbulence is caused by parametric instability of upper hybrid pump. Last decays into daughter upper hybrid wave and ion-acoustic oscillations. In the region above the parametric decay instability threshold the expression for the transformation differential cross-section is obtained and it is shown that the «pump field» term of the transformation coefficient gives the dominant contribution into the cross-section. The transformation coefficient dependence on plasma and pump wave parameters is received.

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INTRODUCTION

As well known in a medium with certain fluctuation level the propagation of electromagnetic waves can lead to radiation of waves with new frequencies and wavenumbers, i.e. scattered waves and also the new type of waves – transformed waves. Obviously the scattering and transformation intensity will be sufficiently large in a non-equilibrium plasma when the level of turbulent fluctuations is much higher than that of thermal noise.

The intensity of nonlinear scattering and transformation processes is defined by such factors as the balance between incident and scattered or transformed wave frequencies, the intensity of incident wave, own plasma characteristics, the level of plasma fluctuations [1, ch.12].

The kinetic fluctuation theory for plasma has been developed in [2–4] and for the case of magnetized plasma with HF pump wave in [5–7]. Notice must be taken that the presence of HF pump can lead the plasma to the turbulent state with high level of plasma fluctuations.

Last experimental investigations demonstrate the important role of plasma fluctuations for studying various nonlinear processes in the plasma.

The fundamental nature of turbulent density fluctuations in W7-X stellarator discharges is investigated experimentally in [8]. In [9] the intermittency of density fluctuations and zonal-flow generation in MAST edge plasmas is studied. The role of density fluctuations in the core turbulent transport of W7-X is analyzed in [10]. Results of new simulations of tokamak edge plasma turbulent fluctuations are presented in [11].

It is shown in [1] that in an unstable plasma in which instability can develop the scattering and transformation intensity may increase without limit near the instability threshold. Particularly the electromagnetic wave transformation into Langmuir wave for a stable magnetized plasma on the resonance fluctuations is investigated. Note that Langmuir, magnetosonic and Alfven fluctuations have been considered.

The theory of the scattering and transformation of electromagnetic waves in a plasma was developed in [2, 12, 13] and is described in detail in [7, 14, 15].

Various transformation processes have been investigated in magnetized turbulent plasma with lower and upper hybrid pump in last works [16–19].

In the present work on the basis of the theory of kinetic fluctuations the transformation of transverse electromagnetic waves into longitudinal Langmuir oscillations is investigated. This process takes place in a turbulent strongly magnetized plasma subjected the influence of an upper hybrid pump. A pump wave is supposed to decay into a daughter upper hybrid and ion-sound waves.

It is shown that the main contribution to the correlator of the electron density is given by the low-frequency ion-sound oscillations. Note that this correlator defines the transformation coefficient.

Transformation coefficient is obtained in the region above the parametric instability threshold when the stabilization mechanism due to nonlinear interaction of plasma fluctuation have been included into consideration. Point out that the expression for the transformation coefficient includes a usual term which exist due to the thermal fluctuations and also the «pump field» terms.

The main objective of this paper is investigation the transformation of transverse electromagnetic wave into a longitudinal Langmuir wave on turbulent plasma density fluctuations in strongly magnetized uniform plasma when the plasma turbulence is caused by parametric instability of upper hybrid pump.

RESULTS

Let us consider the transformation of transverse electromagnetic waves ($\boldsymbol{t}$) into longitudinal Langmuir oscillations ($\boldsymbol{l}$) in uniform, undefined and turbulent magnetized ($\vec{B}_0 = B_0\vec{z}$) plasma subjected the influence of upper hybrid pump wave. In this case ($\boldsymbol{t}\to\boldsymbol{l}$) the differential transformation cross-section may be written in the form [1, ch. 12]

$$d\sum_{t\to l} = \frac{3}{16\pi^2}\left(\frac{e^2}{mc^2}\right)^2 \frac{\omega'^2\omega''^2}{\omega_{pe}^4} R_{tr} \times \\ \times < \delta n_e^2 >_{\vec{q},\Delta\omega} d\omega'' dO, \quad (1)$$

where $\Delta\omega=\omega'-\omega''$ $\vec{q}=\vec{k}'-\vec{k}''$, ω', $\vec{k}'$ and ω'', $\vec{k}''$ are the frequencies and the wave vectors of the incident electromagnetic and transformed Longitudinal waves respectively, dO is the space angle element, and $<\delta n_e^2>_{\Delta\omega,q}$ is the correlator of the electron density fluctuations at the frequency $\Delta\omega$. In formula (1) the factor R_{tr} has the form

$$R_{tr} = \frac{N''^3 \left|\vec{k}''(\hat{\varepsilon}-1)\vec{e}'\right|^2}{N'\left(|\vec{e}'|^2 - \frac{|\vec{k}'\vec{e}'|^2}{k^2}\right)(\vec{k}''\hat{\varepsilon}\vec{k}')},$$

where $\vec{e}'$, $\vec{e}''$, and N',N'' are the polarization vectors and refraction indexes of incident and transformed waves; $\hat{\varepsilon}$ is the tenzor of dielectric plasma permittivity in the magnetic field.

We study the situation when

$$\Delta\omega << \omega' \sim \omega''. \quad (2)$$

In this case one can neglect the interaction between the incident wave and electron velocity, magnetic and electric field fluctuations, i.e we will take into account only the electron density fluctuations. We shall consider fluctuations in magnetized plasma under the influence of pump wave $\vec{E}_0(t) = E_0\vec{y}\cos\omega_0 t$ with the frequency ω_0 which lies in the upper hybrid frequency region.

The important role of parametric instabilities in the upper hybrid resonance region was pointed out in [20, 21].

Let us analyse the case when the pump wave may decay into daughter upper hybrid and ion-acoustic waves

$$\omega_0 = \omega_{UH} + \omega_s, \quad (3)$$

where the upper hybrid frequency is defined by expression $\omega_{UH} \approx \Omega_e\,(1+(\omega_{pe}^2\sin^2(\theta/2\Omega_e^2))$, i.e. we have the case of strongly magnetized plasma at $\omega_{pe} < \Omega_e$. Also assume that $\gamma_{UH} \approx \nu_{ei}$. We note that ω_s is the frequency of ion-acoustic wave.

The correlator of the electron density fluctuation determining the transformation cross-section may be presented in the form:

$$< \delta n_e^2 >_{\Delta\omega,\vec{q}} = \frac{|\varepsilon_E|^2 - \rightleftarrows \varepsilon_E \chi_e^{0*} - \rightleftarrows \varepsilon_E^* \chi_E^0}{|\varepsilon_E(\Delta\omega,\vec{q})|^2} < \delta n_e^2 >^0_{\Delta\omega,\vec{q}} + \\ + \frac{q^2}{16\pi^2 e^2}\frac{|\chi_e^0|^2}{|\varepsilon_E(\Delta\omega,\vec{q})|^2}[< \delta\vec{E}^2 >^0_{\Delta\omega,\vec{q}} + \\ + \frac{\mu^2}{4}|\chi_i^0|^2 \frac{<\delta\vec{E}^2>_{\Delta\omega-\omega_0,\vec{q}}}{|\varepsilon_{-1}|^2}], \quad (4)$$

where $\Delta\omega=\omega_{UH},\omega_s$ for the upper hybrid and ion-acoustic waves, respectively, ε_E is the nonlinear permittivity of the magnetoactive plasma in the presence of HF electric field determined by the expression

$$\varepsilon_E(\omega,\vec{k}) = \varepsilon_0(\omega,\vec{k}) + \frac{\mu^2}{4}\chi_e^0\chi_i^0\left[\frac{1}{\varepsilon_1(\omega+\omega_0,\vec{k})} + \right. \\ \left. + \frac{1}{\varepsilon_{-1}(\omega-\omega_0,\vec{k})}\right],$$

where $\mu = kE_0c/\omega_0B_0$, $\varepsilon_n(\omega+n\omega_0,\vec{k}) = 1+\sum_\alpha \chi_\alpha^n$, $n=0,\pm1$. Here $\chi_\alpha^n = \chi_\alpha(\omega+n\omega_0,\vec{k})$ is the plasma susceptibility of order n and $\alpha=e,i$:

$$\chi_\alpha^n = \frac{4\pi e_\alpha^2 n_\alpha}{k^2} \times \times \int d\vec{p} \sum_r J_r^2\left(\frac{k_\perp v_\perp}{\Omega_\alpha}\right)\frac{1}{\omega - k_{||} v_{||} - r\Omega_\alpha + n\omega_0} \times \\ \left(\frac{r\Omega_\alpha}{v_\perp}\frac{\partial}{\partial p_\perp} + + k_{||}\frac{\partial}{\partial p_{||}}\right) f_\alpha(p_\perp, p_{||}),$$

where J_r is the modified Bessel function of the order n. In the plasma transparency region, where $|Im\varepsilon_E| << |Re\varepsilon_E|$, the multiplier $1/|\varepsilon_E|^2$ may be written in such way

$$\frac{1}{|\varepsilon_E(\Delta\omega,\vec{q})|^2} = \frac{\pi\delta[Re\,\varepsilon_E(\Delta\omega,\vec{q})]}{Im\,\varepsilon_E(\Delta\omega,\vec{q})} = \\ \sum_i \frac{\pi[\delta(\Delta\omega-\omega_{i\vec{q}})+\delta(\Delta\omega+\omega_{i\vec{q}})]}{Im\,\varepsilon_E(\Delta\omega,\vec{q}) \rightleftarrows \times \partial\, Re\,\varepsilon_E/\partial\Delta\omega\big|\Delta\omega=\pm\omega_{i\vec{q}}},$$

where $\omega_{i\vec{q}}$ are the eigen plasma modes ($\omega_{i\vec{q}}=\omega_{UH}$, ω_S).

Taking into account the condition (2) we can see that the main contribution to the correlator of the electron density (4) is given by the low-frequency ion-acoustic oscillations. Then we we can find in the linear approximation the following dependence of transformation coefficient

$$d\sum_{tr} \sim \sigma_T R_{tr}\frac{\delta(\Delta\omega+\omega_s)+\delta(\Delta\omega-\omega_s)}{Im\,\varepsilon_E(\Delta\omega,\vec{q})} d\omega'' d\theta, \quad (5)$$

where $\omega_s=qv_s$ and $v_s=(T_e/m_i)^{1/2}$ is the thermal velocity.

From the expression (5) one notices that two satellites of equal intensity with the frequencies can arise $\omega''=\omega'\pm\omega_s$ in the transformed spectrum.

In the region near the parametric instability threshold we have the anomalous growth of the transformation coefficient (in the linear approximation). Such infinite increase may be explained by the plasma critical fluctuations existence [1].

Therefore we consider the region above the instability threshold, i.e. for $E_0 > E_{th}$, where the threshold field strength value relative to the excitation of the parametric instability E_{th} is given by [20]

$$E_{th}^2 \approx \rightleftarrows \frac{25}{2}\left(\frac{5nm_e}{2m_i}\right)^{\frac{1}{2}}\frac{v_{Te}^2}{c^2}B_0^2\frac{\omega_0^2(\omega_0^2-\Omega_e^2)^2}{\omega_{pe}^4\Omega_e^3}\nu_{ei}.$$

Here γ_s γ_{UH} are the damping rates of ion-acoustic and upper hybrid waves respectively.

In this region we shall take into consideration the nonlinear stabilization mechanism. This mechanism is based on the accounting the additional wave damping which takes place due to the nonlinear interaction of plasma fluctuations. It leads to the stationary state of the turbulent plasma.

In order to obtain the expression for the transformation coefficient in the stationary turbulent state of plasma (above the instability threshold) we introduce the redefined threshold value $\hat{E}_{th}^2 \approx E_{th}^2\nu_{eff}^2/\gamma_s\gamma_{UH}$, where $\nu_{eff} \approx (E_0^2/E_{th}^2)\gamma_s$ is the effective collision frequency which defines the additional wave damping. Such mechanism due to the scattering of charged particles by turbulent plasma fluctuations has been used for describing the stationary plasma state [5].

Note that for the incident electromagnetic wave $k'=\omega'/c$, for the transformed longitudinal Langmuir wave $k''\approx \omega_{pe}/ v_{Te}$. So that we have $k''/ k'\sim c/v_{Te}>>1$, i.e. $q\approx k''$.

Then assuming that

$$\chi_e^0 = \frac{1}{q^2 r_{De}^2}, \chi_i^0 = -\frac{\omega_{pi}^2}{\omega_s^2},$$

$$|\chi_e^0| = |\chi_i^0|, \frac{\partial\, Re\, \varepsilon_E(\omega_s,q)}{\partial \omega_s} \approx \frac{2\omega_{pi}^2}{\omega_s^3}$$

and using the fluctuation-dissipative theorem for the calculation the electric field fluctuations correlators of the non-interacting particles $<\delta\vec{E}^2>^0_{\Delta\omega,\vec{q}}$ and $<\delta\vec{E}^2>^0_{\Delta\omega-\omega_0,\vec{q}}$, one can obtain the expression for the differential transformation cross-section

$$\frac{d\sum_\pm}{d\theta} \approx \frac{3}{8\pi}\sigma_T \frac{\omega'^2(\omega'\pm q v_s)^2}{\omega_{pe}^4} R_{tr} \frac{q^2 T_e}{e^2}\frac{\omega_{pi}^2}{\omega_s^2} \times [1 +$$

$$+ \frac{\mu^2}{4}\frac{1}{q^2 r_{De}^2}\frac{\omega_{pe}^2}{2\nu_{ei}\omega_{UH}}\left(1+\frac{1}{q^2 r_{De}^2}\frac{\omega_s^4}{2\gamma_s\omega_{UH}\omega_{pi}^2}\right) +$$

$$+ \frac{\mu^4}{64}\frac{1}{q^4 r_{De}^4}\frac{\omega_{pe}^4}{\nu_{ei}^2\omega_{UH}^2}\,. \tag{6}$$

We note that the expression (6) includes an usual term which exist due to the thermal fluctuations and also the «pump field» terms. The calculations show that for typical parameters of a hot plasma μ ~10^{-1}, $qr_{De}\approx 2\cdot 10^{-1}$, $B_0\approx 50$ kG, $T_0\sim 5$ keV, $n\approx 10^1\,\mathrm{cm}^{-3}$ the “pump field” part of cross section of the transformation exceeds the one due to the transformation of thermal noise by several order of magnitude.

CONCLUSIONS

The novelty of the article is following. In [22] the analogous type of transformation process ($t\to l$) have been investigated but in the presence of lower hybrid pump wave. In [17] we considered the transformation of another type ($l\to t$) for the same parametric decay (3) but for the case of weakly magnetized plasma, i.e. $\omega_{UH}\approx(\omega_{pe}^2+\Omega_e^2)^{1/2}$ at $\omega_{pe}>\Omega_e$.

Notice must be taken that now authors investigate the $(t\to l)$ transformation process when the plasma turbulence is caused by parametric instability of upper hybrid pump with frequency $\omega_0\sim\omega_{UH}$ where $\omega_{UH}\approx\Omega_e(1+(\omega_{pe}^2 \sin^2(\theta/2\Omega_e^2))$, i.e. we have the case of strongly magnetized plasma at $\omega_{pe}<\Omega_e$.

The results of this paper should be useful for understanding the processes of electromagnetic wave transformation in the laboratory plasma with upper hybrid pump and also for experimental investigations using transformation and scattering techniques for studying the influence of turbulent density fluctuations in thermonuclear plasma.

Also note that study of wave transformation and scattering is an important method for laboratory and space plasma diagnostics.

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ПРОЦЕСИ ТРАНСФОРМАЦІЇ В СИЛЬНО ЗАМАГНІЧЕНІЙ ТУРБУЛЕНТНІЙ ПЛАЗМІ З ВЕРХНЬОГІБРИДНОЮ НАКАЧКОЮ

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На основі кінетичної теорії флуктуацій досліджено процес трансформації поперечної електромагнітної хвилі у повздовжню ленгмюрівську в сильно замагніченій однорідній плазмі, коли турбулентність плазми спричинюється параметричною нестійкістю верхньогібридної хвилі накачки. Остання розпадається на дочірню верхньогібридну хвилю та іонно-звукові коливання. У запороговій області параметричної розпадної нестійкості отримано вираз для диференційного перерізу трансформації та показано, що домінантний внесок у переріз здійснюється членом, який залежить від амплітуди поля накачки. Знайдена залежність коефіцієнта трансформації від параметрів плазми і хвилі накачки.