MODELLING ELECTRON-ION PARAMETRIC INSTABILITY AND TURBULENCE OF PLASMA IN THE ION CYCLOTRON FREQUENCY RANGE

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An alternating electric field with the frequency of the order of ion cyclotron one may induce various parametric instabilities of both kinetic and hydrodynamic types [1-3]. The modes corresponding to ion cyclotron oscillations and electron sound ones, whose dispersion is modified by alternating electric field, are unstable. Modelling these instabilities by means of macroparticle technique has shown the presence of the fast turbulent heating of ions across the magnetic field and electrons - along it [4]. The cyclotron resonance broadening is responsible for saturation of the oscillations at the nonlinear stage [5]. The nonlinear effects increase fast with amplitude growth of the pumping field, namely, with growth of parameter $u/v_{Ti}(0)$, where u is the amplitude of the velocity of the electron motion relative to ions in the field of the pumping wave, $v_{Ti}(0)$ is the initial thermal velocity of ions. In this report the results of the further research of these parametric instabilities are presented. Here we describe the results of comparison of the linear analysis of this instability with the spectral characteristics of the turbulence to appear. It is shown that the development of the turbulence is accompanied by the dynamic chaos to appear both in the particle motion and in the evolution of the selfconsistent electric fields.

The turbulence arises under the action of the pumping electric field with an amplitude corresponding to the amplitude of oscillations of velocity of the electrons relative to ions $u/v_{Ti}(0) = 0.9$. The time dependence of amplitude of the maximum Fourier harmonic is shown in Fig. 1a and its frequency spectrum is in Fig. 1b. The numerical solution of the linear parametric dispersion equation is given in Fig. 2. In the frequency range $n\omega_{ci} < \omega(k) < (n+1)\omega_{ci}$, ($n \geq 2$) the dispersion equation has four roots corresponding to the frequencies of the ion Bernstein waves $\omega = \omega(k)$ superposed with the harmonics of the external field frequency $\omega = N\omega_0$, where $\omega_0 = 1.2\omega_{ci}$. These frequencies are parametrically unstable. The frequency shift $|\omega(k) - N\omega_0|$ and the growth rate have a maximum in the region, where the frequency $N\omega_0$ coincides with IBW-frequency.

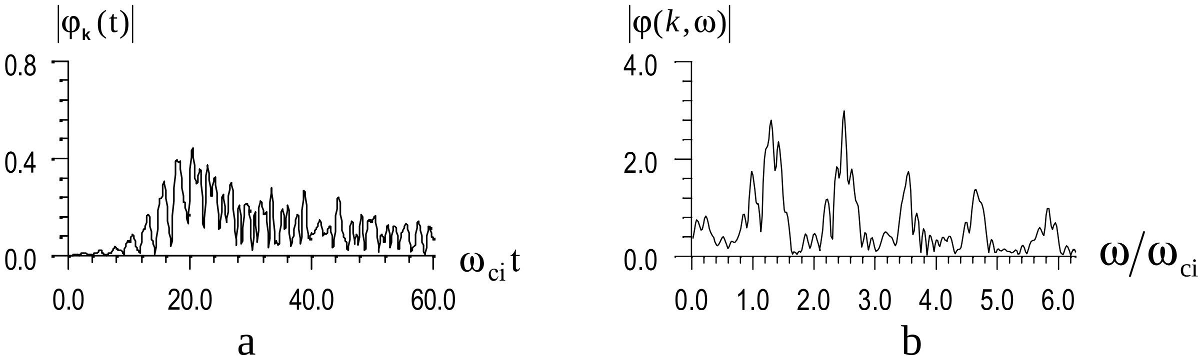

Fig 1. a} - time behaviour of amplitude of the most unstable mode and b) - frequency spectrum of this mode ($\omega_0 / \omega_{ci} = 1.2$, $k_\perp \rho_{Li} = 1$; $k_{||}\rho_{Li} = 0.05$).

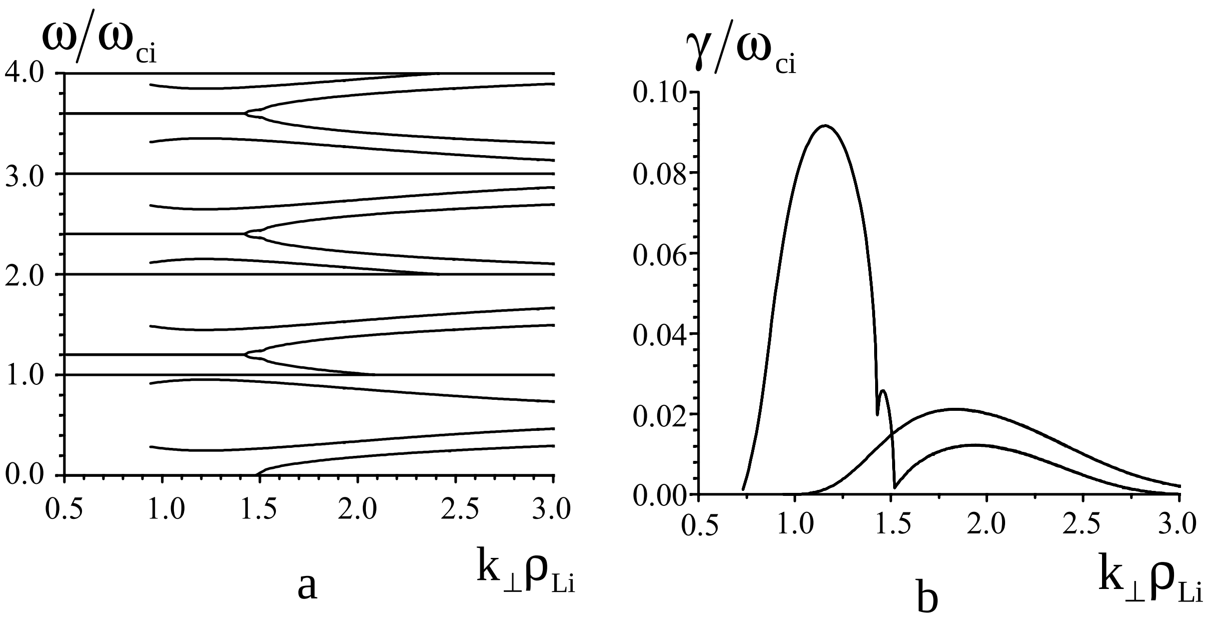

Fig. 2. The solution of the linear parametric dispersion equation in the case $\omega_0 = 1.2\omega_{ci}$, $u/v_{Ti}(0) = 0.9$, $k_{||}\rho_{Li} = 0.05$: a) - frequencies and b) - growth rate of the unstable oscillations.

The frequency shift and the growth rate are determined by the electron sound frequency $\omega_s \sim k_{||} v_{Te}$, $T_e \sim T_i$ (see Fig. 2a). For $\omega_{ci} < \omega < 2\omega_{ci}$ there are three roots of the linear dispersion equation only. The fourth root lies in the region which is situated somewhat below ω_{ci}. The clearly expressed peaks in Fig 1b and the first maximum of the growth rate in Fig. 2b correspond to the frequencies $\omega \approx N\omega_0$. The split of the peaks is related to the second unstable mode arising in the range $\omega > \omega_{ci}$ with the frequency more than $\omega \approx N\omega_0$. This mode has the growth rate exceeding one for the wave with the frequency $\omega \approx N\omega_0$ in the region $k\rho_{Li} \geq 1.5$ (the second maximum in Fig. 2b). With the temperature increase the parameter $k\rho_{Li}$ for given k tends to this region. There are unstable electron sound oscillations with the frequency $\omega(k) \approx k_{||} v_{Te}$ ($q_0 = (m_i/m_e)(k_{||}/k)^2 \le 0.2$) in the range of the frequencies below ω_{ci}. The oscillations with this frequency can relate to the first peak in Fig. 1b at $\omega/\omega_{ci} \approx 0.2 \div 0.3$. The peak in Fig. 1b corresponding to the somewhat lesser frequency than ω_{ci} correlates with the frequency adjacent from below to ω_{ci}. This frequency corresponds to the second branch of the parametrically unstable oscillations, that appear due to parametric relation between Bernstein mode having frequency $\omega_{ci} < \omega(k) < 2\,\omega_{ci}$ and the frequency of the pumping field. The frequency spectrum in Fig. 1b is obtained by means of integration of the space Fourier harmonic $\varphi_k(t)$ over the total time period of modelling and, consequently, reflects possible broadening of the resonant frequencies because of the nonlinear wave interaction.

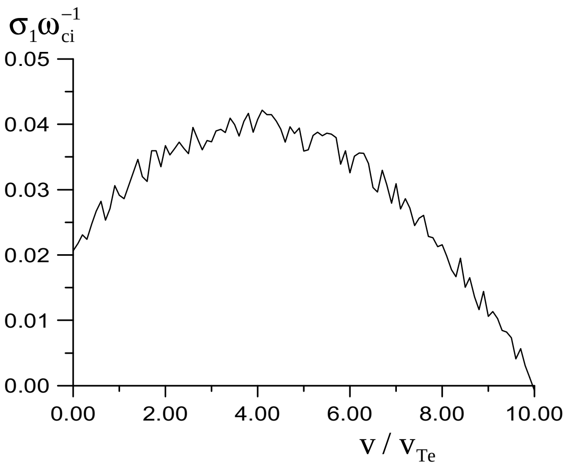

Fig. 3. Behaviour of the maximum Liapunov's factor.

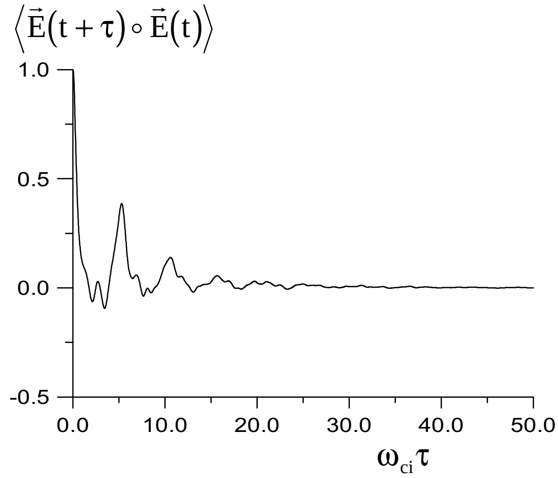

Fig. 4. Autocorrelation function of the selfconsistent electric field.

The particle motion under the action of the field of unstable oscillations is accompanied by the dynamic chaos arising at the nonlinear stage. The behaviour of the maximum Liapunov's factor versus initial velocity of electron is shown in Fig. 3. In the broad range of frequencies the maximum Liapunov's factor is seen to have the order of value $0.02 \div 0.04\ \omega_{ci}^{-1}$ at $v/v_{Te}(0) = 0 \div 8$, i.e. it is the order of linear growth rate.

In Fig. 4 autocorrelation function of the selfconsistent electric field is shown. It results from this that the correlation of the fields disappears during several periods of cyclotron oscillations. It means that the field decays into wave packets with random phases. Figure 5 can serve as an illustration for the stochastic motion of particles. There the deformation of the small phase volume is shown. At the initial moment the volume has the shape of a circle and the size of one ion Larmor radius in space and one ion thermal velocity in the velocity space along the magnetic field.

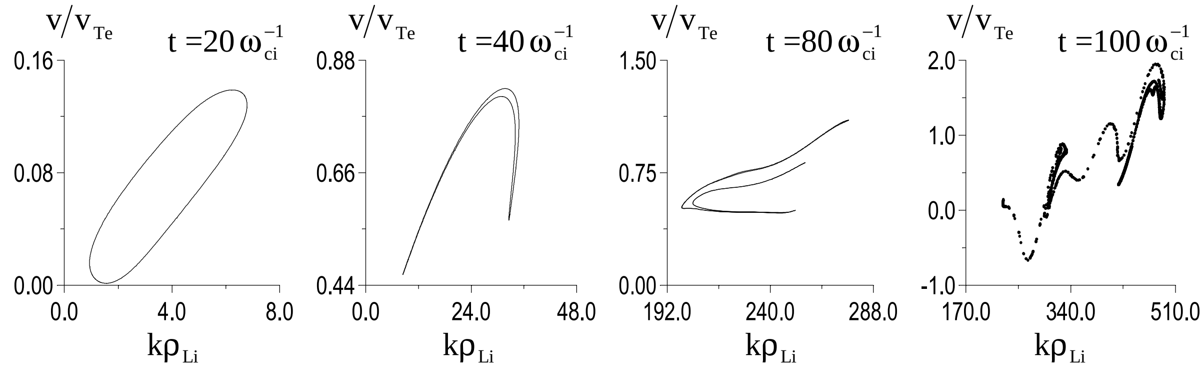

Fig. 5. Deformation of a shape of the small phase volume.

At first the deformation leads to the circle to be transformed into the oval ($t = 20\,\omega_{ci}^{-1}$), then the oval stretches into the thin boomerang ($t = 40\,\omega_{ci}^{-1}$) and then ($t = 80\,\omega_{ci}^{-1}$) the boomerang assumes a shape of two very thin threads. At $t = 100\,\omega_{ci}^{-1}$ these threads become longer and, being not crossed, curl up several times, occupying larger area in phase space. Similar phenomena appear also at the pumping frequencies below ω_{ci}.

The carried out research allows to draw the following conclusions. Parametric turbulence in the frequency range of the order of ion cyclotron one and with velocity of oscillations of electrons relative to ions $\sim v_{Ti}$ leads to:

1) the excitation of the shortwave ion cyclotron oscillations (ion Bernstein waves) and the electron sound oscillations accompanied by heating of electrons and ions and saturation of the oscillations in strongly nonlinear regime,
2) heating of electrons and ions in the regime of the dynamic chaos in particle motion and decorrelation of the selfconsistent electric field.

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