MODELLING OF PARAMETRIC KINETIC ION-ACOUSTIC INSTABILITY IN HELICON DISCHARGE

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A computer simulation of the development of the parametric kinetic ion-acoustic instability is carried out for the helicon discharge conditions by the "particle in cell" method. Linear and nonlinear stages of the ion-acoustic instability and turbulence are investigated for the typical parameters of the helicon plasma. It is shown that the high efficiency of the helicon plasma sources can relate to development of both short and long wavelength kinetic ion-acoustic parametric instabilities and the turbulent heating of electrons and ions caused by the ion-acoustic turbulence can be one of the dominant mechanisms of the pumping wave energy absorption in the helicon plasma.

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INTRODUCTION

The relative motion of plasma components across the magnetic field can cause many instabilities of the beam or parametric kind. Invoked by these instabilities plasma turbulence is an origin of the numerous abnormal phenomena in plasma: abnormal electric resistance, quick relaxation of the charge particles beams, abnormal pumping field energy absorption, turbulent heating of electrons and ions, plasma ionization and so on. Such beam or parametric ion-acoustic instabilities can arise in the helicon plasma sources widely used in the plasma technologies for plasma production.

The first attempts to explain the high efficiency of the helicon waves absorption by the conventional absorption mechanisms did not succeed. The problem is the conventional absorption mechanisms such as collisional one, Cherenkov's absorption and cyclotron resonance are ineffective for the helicon waves. However the nonlinear mechanism, which can explain this phenomena, exists. It is well known that the ion-acoustic (IA) activity is the phenomena commonly observed in the helicon sources. For the first time it was predicted in the theoretical papers [1, 2], where it is shown that IA turbulence can arise as a result of the kinetic parametric instability development and leads to the plasma heating. In addition the IA turbulence was revealed in many experiments using both the microwave diagnostic [3, 4] and the probe measurements [5].

In present paper we investigate the nonlinear stage of the IA parametric instability and turbulence in the helicon plasma by means of numerical simulation with PIC code [6].

This paper is organized as follows. In the section 1 we analyze the linear stage of the IA parametric instability for the estimation of the characteristic space and frequency scales of the IA parametric instability. In the section 2 we present the results of the computer simulation of this instability, and then we draw the conclusions.

1. LINEAR STAGE OF IA PARAMETRIC INSTABILITY IN HELICON PLASMA

If the relative motion of electrons versus ions caused by the pumping wave with the frequency of the order of the ion sound one, the possibility of excitation of the IA instability of the kinetic kind appears [7]. This instability are exited by the electrons moving along the magnetic field with the velocity $v_{||}$ that is equal to the phase velocity of the beats between the pumping field and the unstable oscillations. The frequency of these beats is equal to $\omega_s - p\omega_0$, and the longitudinal wave number is equal to $k_{||} - pk_{||0}$, where ω_0 and $k_{||0}$ is the frequency and the longitudinal wave number of the pumping field, and p is an integer number. The velocity of the resonant electron is equal to $v_{||} = (\omega_s - p\omega_0)/(k_{||} - pk_{||0})$. The dispersion equation that determines the frequency of the ion sound and the contribution of the electrons into the growth rate reads [1]

$$1 - \frac{\omega_{pi}^2}{\omega^2} + \frac{\omega_{pe}^2}{k^2 v_{Te}^2}\left\{1 + i\sqrt{\pi} I_0\left(k^2\rho_e^2\right)e^{-k^2\rho_e^2} \times \sum_{p=-\infty}^{\infty} J_p^2(a_E) z_e^p W\left(z_e^p\right)\right\} = 0 , \qquad (1)$$

where $z_e^p = (\omega - p\omega_0)/\left(\sqrt{2}\left|k_{||} - k_{||0} p\right| v_{Te}\right)$. The argument of the Bessel functions a_E is of the order of magnitude $a_E \sim k_0 u_\perp/\omega_0$, were $u_\perp$ is the amplitude of the electron velocity in the pumping wave field. The dispersion equation (1) is valid for the short wavelength oscillations, $k_\perp \rho_e >> 1$. In this case the electron terms, which determine the dispersion and growth rate of the ion sound, are proportional to the small parameter $I_0\left(k^2\rho_e^2\right)e^{-k^2\rho_e^2} \approx \left(\sqrt{2\pi} k\rho_e\right)^{-1}$. As we can see, in the case of short wavelength oscillations the parametric dispersion equation is reduced to the equality of the diagonal element of the infinity determinant with zero.

In Fig. 1 the linear growth rate of the short wavelength IA parametric instability are shown. It was numerically obtained from the equation (1) for the pumping wave frequency $\omega_0/\sqrt{\omega_{ce}\omega_{ci}} = 1.2$. The relation of plasma frequency to cyclotron one is $\omega_{pe}^2/\omega_{ce}^2 = 25$. Such choice of the parameter $\omega_{pe}^2/\omega_{ce}^2$ corresponds to the helicon branch of the oscillations usually considered under the condition $\omega_{pe}^2 >> \omega_{ce}^2$. The relation of the electron temperature to the ion one is

$T_e/T_i = 10$. The relative velocity of the electron oscillations considerably exceeds the ion sound velocity, $u/v_s = 5$. These parameters correspond to the experimental data. The operation gas is argon usually used in many experiments. The curves in Fig. 1 correspond to the values of $\cos\theta$ from 0.06….0.09 with the step 0.005, where θ is the angle between the magnetic field and the wave vector.

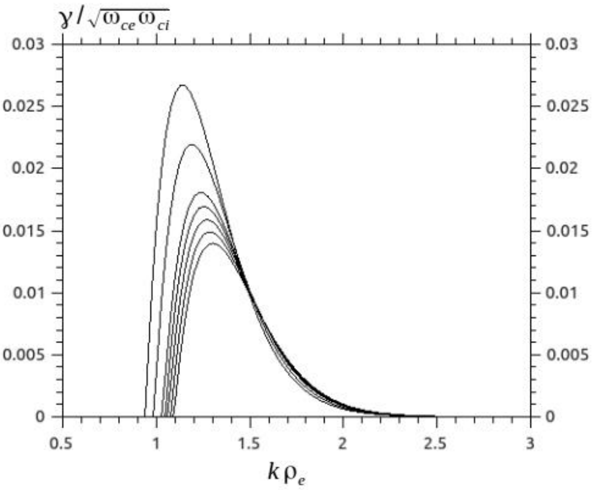

Fig. 1. Growth rate of the short wavelength IA instability

One can see in Fig. 1 the maximum value of the growth rate increases with decreasing of $\cos\theta$ up to the value $\cos\theta = 0.06$. At this $\cos\theta$ value the maximum growth rate is $\gamma_{\max} \approx 0.027\sqrt{\omega_{ce}\omega_{ci}}$. This maximum growth rate value is reached at $k\rho_e \approx 1.17$. In this case the frequency is $\omega \approx 1.15\sqrt{\omega_{ce}\omega_{ci}}$, and the beat with p=2 ($p\omega_0 > \omega$) is responsible for excitation of the unstable oscillations. For the maximum growth rate the value $|z_{ep}| \sim 1$. For the chosen numerical parameters the interaction of the resonant electrons, which velocity is of the order of the electron thermal velocity, with the beats is essential.

Separation of the unstable short wavelength IA oscillations is possible only for the "weak" magnetic fields, when $\omega_0 > \sqrt{\omega_{ce}\omega_{ci}}$. But there are a number of experiments where the magnetic field is relatively "strong", $\omega_0 \lesssim \sqrt{\omega_{ce}\omega_{ci}}$. In this case it is necessary to consider the long wavelength, $k\rho_e \lesssim 1$, IA instability. For the long wavelength IA instability it is not sufficient to consider only the diagonal terms but the nondiagonal ones should be taken in account too. So we consider the full parametric dispersion equation that is the equality of the infinite determinant with zero [7].

$$D = \det\|a_{mn}\|_{m,n=-\infty}^{\infty} = 0, \qquad (2)$$

where

$$a_{mn} = \delta_{mn} + \frac{\exp\left[-i(n-m)(\delta+\pi)\right]}{1+\delta\varepsilon_i(\omega - m\omega_o, \mathbf{k})} \sum_{p=-\infty}^{\infty} J_{p+m}(a_e) \times$$
$$\times J_{p+n}(a_E)\,\delta\varepsilon_e(\omega + p\omega_o, \mathbf{k} + p\mathbf{k}_{\|0}).$$

In Fig. 2 the behavior of the linear growth rate of the long wavelength IA instability against the wave number is presented. It is the result of the numerical solution of the equation (2) with following parameters: $\omega_0/\sqrt{\omega_{ce}\omega_{ci}} = 0{,}6$, $\omega_{pe}^2/\omega_{ce}^2 = 25$, $T_e/T_i = 10$, $u/v_s = 5$. The curves in Fig. 2 correspond to the values of $\cos\theta$ from 0.01 to 0.05 with the step 0.005, The operation gas is hydrogen. As a rule in helicon sources argon is used as an operation gas. But the result of the calculation, as easy to be sure, does not depend from the mass of the operation gas when $kr_{De} << 1$ under the assumption that $\omega_0/\sqrt{\omega_{ce}\omega_{ci}}$ and u/v_s are fixed.

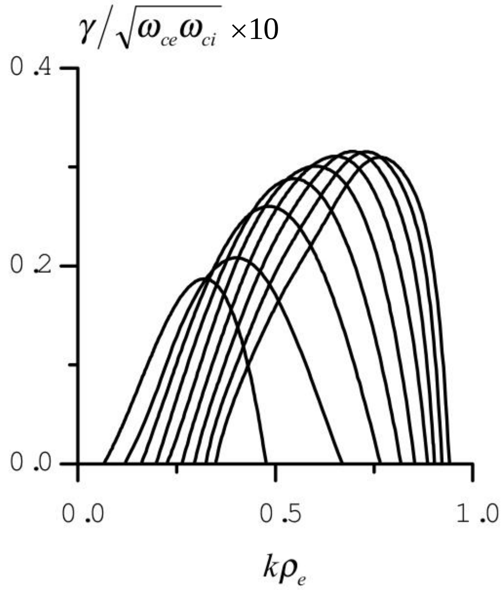

Fig. 2. Growth rate of the long wavelength IA instability

One can see in Fig. 2 that with the $\cos\theta$ growth up to the value 0.045 maximum value of the growth rate increases and reaches the value $\gamma_{\max} \approx 0.03\sqrt{\omega_{ce}\omega_{ci}}$. This maximum value is reached at $k\rho_e \approx 0{,}75$. In this case the frequency is equal to $0{,}9\sqrt{\omega_{ce}\omega_{ci}}$. For the maximum growth rate $|z_{ep}| \sim 1$ as in the case of short wavelength IA instability, and the interaction of the resonant electrons with the beats is essential too.

2. NUMERICAL SIMULATION RESULTS

For the numerical simulation of the nonlinear stage of IA parametric instability in the helicon plasma source the PIC code [6] was used. The simulation parameters was chosen in the following way: the plasma density $n_0 = 10^{12}\,\text{cm}^{-3}$, the external magnetic filed $B_0 = 100$ G, the electron temperature T_{e0} =3 eV, the ion temperature T_{i0} =0.1 T_{e0} =0.3 eV , the pumping wave frequency $\omega_0 = 1.2\omega_{LH}$. The relative velocity of the electrons with respect to the ions equals to $5 \cdot v_s$, where v_s is the ion sound velocity. Then, the parameter $q = \omega_{pe}/\omega_{ce}$ =32. The operation gas is argon. In Fig. 3 the amplitude of the relative velocity of the electrons and ions is shown during one pumping wave period. One can see that the average velocity amplitude is modified by the cyclotron oscillations of the electrons.

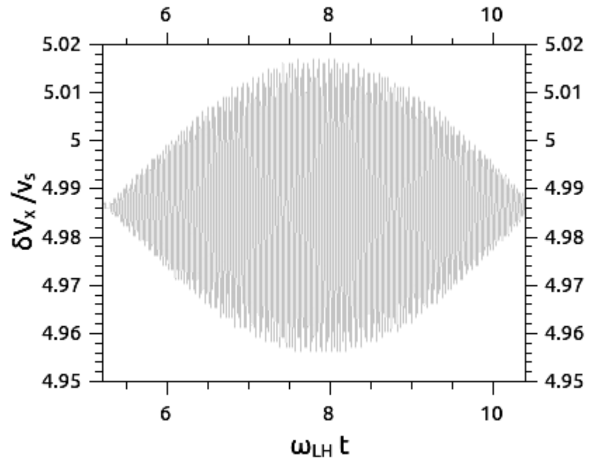

Fig. 3. Relative velocity of the electrons and ions

The time behavior of the electric field energy density normalized on the initial thermal energy of the electrons is shown in Fig. 4. The electric field energy firstly exponential increases reaching the maximum level and then, after a number of the relaxation oscillations, decreases together with the value of $u/v_s(t)$. The curve 1 in Fig. 4 is proportional to $\exp(0.06 \cdot \omega_{LH}(t - t_0))$. It agrees with the maximum growth rate in Fig. 1. At the final stage the value of E^2/n_0T_{e0} reaches a quasi stationary level.

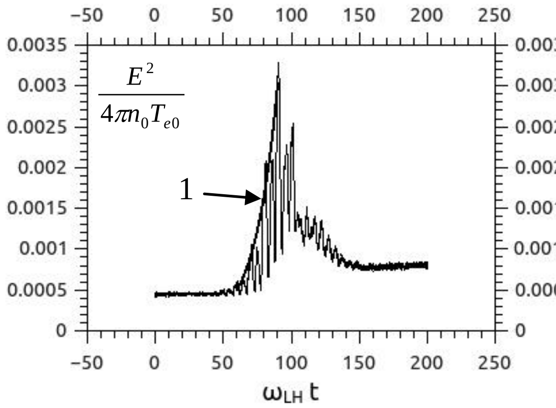

Fig. 4. Electric field energy density

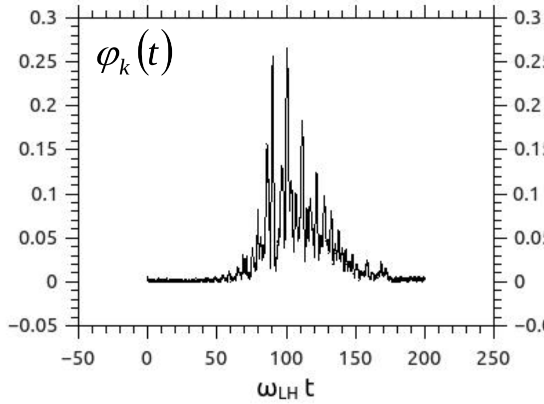

Fig. 5. Most unstable electric field mode

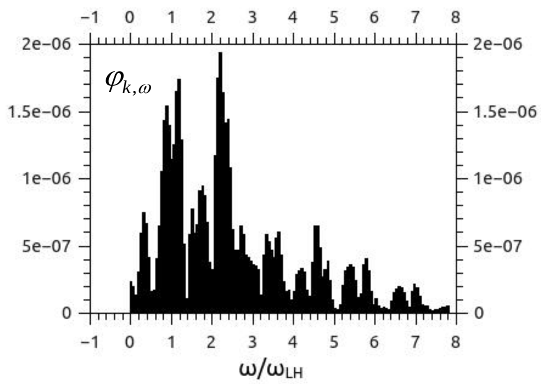

Fig. 6. Frequency spectrum of the most unstable mode

The time behavior of the amplitude of the most unstable ($k\rho_e \approx 1.17$) Fourier harmonic of the electric potential is presented in Fig. 5, and correspondent frequency spectrum is shown in Fig. 6. The frequency spectrum is computed by means of integration of the space Fourier harmonic $\varphi_k(t)$ over the all computation time interval and therefore reflects the possible broadening of the resonant frequencies.

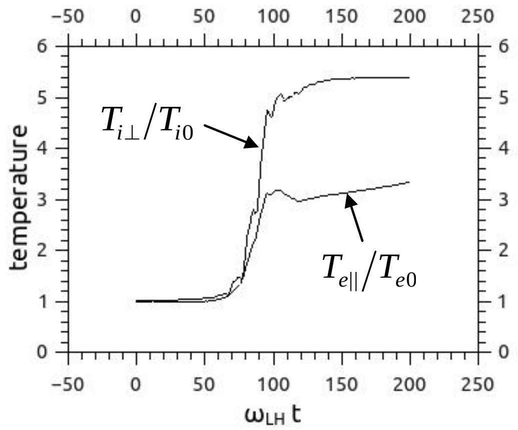

Fig. 7. Temperature growth

In Fig. 7 the time dependence of the longitudinal electron temperature and transversal ion temperature is sown. The transversal ion temperature becomes more than 5 times greater than initial one. The longitudinal electron temperature becomes more than 3 times greater than the initial one and continues to increase in the quasi stationary state.

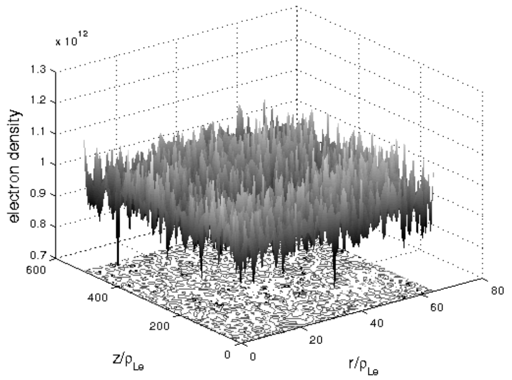

Fig. 8. Electron density

Fig. 8 presents the pattern of the turbulent pulsation of the electron density at quasi stationary state. The fluctuation level is found to be about 10% of the average value.

When the IA instability reaches the saturation level the ion velocity distribution becomes non isotropic one. As shown in Fig. 9, the initial Maxwellian ion velocity distribution function (a) firstly stretches in some direction (b) and then the tail of the accelerated electrons appears on it (c).

CONCLUSIONS

The carried out investigation shows that high efficiency of the helicon plasma sources can relate to the development of both the short wavelength and long wavelength kinetic IA parametric instabilities. The computer simulation by means of the PIC code gives the evidence that the electron and ion turbulent heating can be one of the dominant mechanisms of the pumping field energy absorption in the helicon sources.

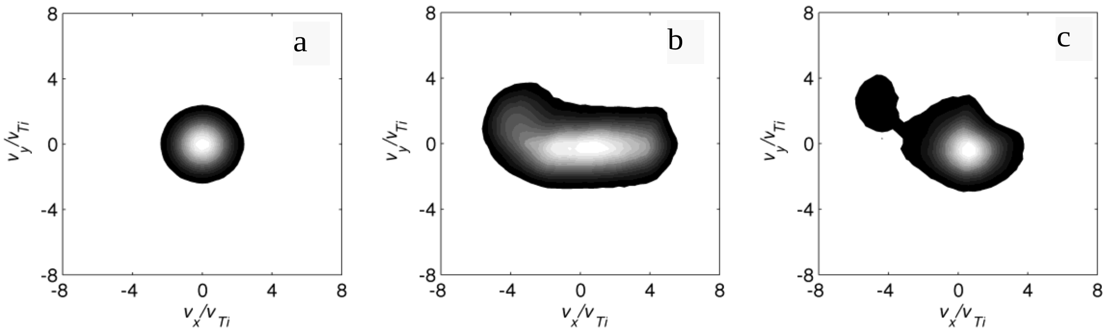

Fig. 9. Ion velocity distribution

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МОДЕЛИРОВАНИЕ ПАРАМЕТРИЧЕСКОЙ КИНЕТИЧЕСКОЙ ИОННО-ЗВУКОВОЙ НЕУСТОЙЧИВОСТИ В ГЕЛИКОННОМ РАЗРЯДЕ

В.В. Ольшанский

Методом "particle in cell" проведено моделирование развития параметрической кинетической ионно-звуковой неустойчивости в условиях геликонного разряда. Исследованы линейная и нелинейная стадии ионно-звуковой неустойчивости и турбулентности при типичных значениях параметров геликонной плазмы. Показано, что высокая эффективность геликонных источников плазмы может быть связана с развитием как коротковолновой, так и длинноволновой кинетической ионно-звуковой неустойчивости, и турбулентный нагрев электронов и ионов, обусловленный ионно-звуковой турбулентностью, может быть одним из доминирующих механизмов поглощения энергии волны накачки в геликонной плазме.

МОДЕЛЮВАННЯ ПАРАМЕТРИЧНОЇ КІНЕТИЧНОЇ ІОННО-ЗВУКОВОЇ НЕСТІЙКОСТІ В ГЕЛІКОННОМУ РОЗРЯДІ

В.В. Ольшанський

Методом "particle in cell" проведено моделювання розвитку параметричної кінетичної іонно-звукової нестійкості в умовах геліконного розряду. Досліджені лінійна і нелінійна стадії іонно-звукової нестійкості і турбулентності при типових значеннях параметрів геліконної плазми. Показано, що висока ефективність геліконних джерел плазми може бути пов'язана з розвитком як короткохвильової, так і довгохвильової кінетичної іонно-звукової нестійкості, і турбулентне нагрівання електронів та іонів, зумовлене іонно-звуковою турбулентністю, може бути одним з домінуючих механізмів поглинання енергії хвилі накачки в геліконній плазмі.