INVESTIGATION OF POSIBILITY OF ENERGY TRANSFER TO PLASMA IONS BY OSCILLATIONS WITH LARGE AMPLITUDE ON FREQUENCY OF ELECTRON CYCLOTRON RESONANCE IN MAGNETIC TRAP

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Process of action of powerful transverse electromagnetic wave on plasma in the magnetic trap is studied theoretically and experimentally. Interaction of wave-wave type is taken into account in the theoretical model. Investigation is based on three wave interaction. The cascades of three wave interaction described too. In the experiment the wave spectrums exciting in plasma were studied and it was shown enough fast appearance of energetic ions flows. There is a enough good agreement theoretical and experimental results.

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INTRODUCTION

Processes taking place in plasma placed in open trap when intensive external electromagnetic waves acts on this plasma are numerous and various. It is needed to distinguish processes of interaction of types of wave-wave and wave-particle among them. In many known cases these processes may consider separately. Moreover processes of type of wave-particle studied enough well (see [1-8]) and basically touch of interaction external waves with electron subsystem of plasma. In all works, devoted to interaction of external waves with plasma ion component almost did not took into account. It taking into account was considered as secondary effect. In this work we will show theoretically and experimentally that there is some chain of physical processes (decays) that may first of all appear as oscillation excitation that characteristics defined by ions.

Below in section 2 decay process of external intensive transverse electromagnetic wave into new transverse one and low frequency one was considered. It characteristic is defined by ions. Most important result of this section is fact that matrix element of wave interaction is the more the less is frequency of LF wave. In this section, the description of cascades are given. In the third section the results of experiment are presented. The spectral characteristics of waves are given and appearance of flows of energetic plasma ions is given too. In conclusion, the considering processes are described. A good qualitative agreement between theory and experiment is shown.

1. BASIC EQUATIONS AND THEORETICAL ANALYSIS

1.1. FEATURES OF TRANSFER TO CHAOTIC REGIME

Phenomena observing in experiment may be induced by stochastic three wave decays. The theoretical and numerical investigations of chaotic decays considered in detail in works [1-8]. Cascades of such processes consider in [7].

Nonlinear interaction of waves in plasma is well known area. Usually studying of processes of such in teraction is limited by weakly nonlinear approach. Amplitudes of these waves slow varying in time and space. In more detail simplest case studied when three waves take part in interaction. The example of such process is decay when wave with high frequency transfers into two new ones with less frequencies. In works [5, 6] it was shown that decay may be chaotic. In this works the criterion of appearance of chaotic regime was given.

Equations describing decay may be obtained from Maxwell ones for components of electromagnetic field and hydrodynamics equations for electrons and ions of plasma and have form:

$$\frac{\partial a_1}{\partial t} = V a_2 a_3, \ \frac{\partial a_2}{\partial t} = -V a_1 a_3^*, \ \frac{\partial^2 a_3}{\partial t^2} + \omega_3^2 a_3 = -V a_1 a_2^*. \quad (1)$$

Values a_1, a_2, a_3 are proportional to slowly varying amplitudes of eigen waves of electrodynamics system taking part in decay, V – matrix element of nonlinear interaction, the frequencies of these wave equal correspondingly to ω_1, ω_2, ω_3, and wave vectors are $\vec{k}_1$, $\vec{k}_2$, $\vec{k}_3$, which satisfy to synchronism conditions:

$$\omega_1 = \omega_2 + \omega_3, \quad \vec{k}_1 = \vec{k}_2 + \vec{k}_3. \quad (2)$$

The set of equations (1) describes decay of HF wave 1 into more low frequency ones 2 and 3.

In equation (1) took into account that third wave self may change slowly. So we conserve it oscillation properties. In physical system described by equations (1) may exist chaotic regimes. It arise when amplitudes of decaying wave is enough large, that increment of decay instability is larger than frequency of LF wave. Such estimation was obtained in works [5, 6]. We may use this estimation.

$$a_{10} > \min(\omega_2, \omega_3)/V, \quad (3)$$

where a_{10} – initial amplitude of decaying wave.

Features of interacting waves did not took into account in expression (3). Earlier relation (3) was concretized for waves, which dispersion properties defined by electron component of plasma only. In this case frequencies and wave numbers satisfy to next relation:

$$\omega_1 \approx \omega_2 >> \omega_3, \ |k_1| \approx |k_2| \approx |k_3|. \quad (4)$$

We are interested by magnetactive plasma. As ω_1 and ω_2 it is possible to consider, for example, any closed by frequencies HF electromagnetic waves. In this work we consider decays where dispersion properties of low frequency wave are defined by ion dynamics. In particular it may belong to Alfven or fast magnetosound branches.

Analytical dependence for matrix element of nonlinear interaction versus frequency of one of waves taking part in interaction has form

$$V = \frac{\omega_{pe}^2 e k_3}{m_e c^2 D_1} \frac{1}{\omega_3^2}, \quad (5)$$

where e, m_e – charge and mass of electron; c – light velocity; ω_{pe} – Langmuir frequency; $D_1(\omega_1)$ – coefficient depending of dispersion properties of decaying wave only. It is needed to note that value of matrix element is inversely proportional to square of low frequency. For threshold of stochasticity appearance we obtain next expression:

$$E_{th} = \omega_3^3 \frac{m_e c^2 D_1}{\omega_{pe}^2 e k_3}. \quad (6)$$

It is follows from (6) that strength of HF wave needed for arising of stochastic decay is abnormally low for decay of waves which properties are defined by plasma ions. As it seen, the value of strength of decaying HF wave needed for arising of regime with dynamics chaos will be proportional to cube of frequency of LF wave.

1.2. DECAY DYNAMICS IN STOCHASTIC REGIME

In the many cases wave dynamics in stochastic regime is characterized that most sensitive and "mobile" (easily variable) characteristics of interacting waves are their phases. The set of equations for square of modules of slowly varying complex amplitudes with random phases will have form

$$\frac{\partial N_1}{\partial t} = W\left(N_2 N_3 - N_1 N_2 - N_1 N_3\right), \qquad \frac{\partial N_2}{\partial t} = \frac{\partial N_3}{\partial t} = -\frac{\partial N_1}{\partial t}, \quad (7)$$

where $N_i = |a_i|^2$, $W = V^2\tau$, τ – time correlation between phases [1-3]. When this set of equations was obtained it is supposed that third equation of set (1) was shortened.

As it seen from set of equation (7) unlike from regular regime, in stochastic one there are stationary points. There are as stable as unstable ones.. It may show that regardless of initial conditions, solution tends to stable stationary point, which depends on initial condition. It may show when conditions (4) is satisfied and $N_{10} >> N_{20} \approx N_{30}$ (N_{i0} – initial values of N_i) in the stationary point square of amplitude module of decaying wave has one third part of it initial value. Values of amplitudes modules square for second and third waves have two third parts of initial values of corresponding one of decaying wave.

1.3. CASCADES OF DECAYING PROCESSES

The character features of regular and stochastic decays and transfer from regular to chaotic regime have been considered above. It was supposed that decays are isolated. But in real experiment synchronism conditions (2) may be satisfied for large number of triplets. Such scenario of decay is possible. Most high frequency wave decays into new HF and LF ones. Latter new HF wave decays into other HF and LF ones and so on. In this way the process of nonlinear interaction may be cascade. The example of such cascade was considered in works [1, 7]. Electromagnetic field in plasma in this case is sum of nonlinearly interacting waves. This field may be presented in such form:

$$E_h = \sum_n A_n \exp\left[i\left(\omega_0 + n\cdot\Omega\right)t\right], \qquad E_l = \sum_n A_n \exp\left[i\Omega t\right], \quad (8)$$

where E_h – high frequency field that is sum of *n* decaying waves with frequencies $\omega_0 + n\cdot\Omega$; ω_0 – lowest frequency from HF waves; Ω – frequency of LF waves that may have different wave number. Equations for complex slowly varying amplitudes of waves taking part in cascade of decay processes may present in next form:

$$\frac{\partial A_1}{\partial t} = V_{10} A_1 B_0^*, \ \frac{\partial A_2}{\partial t} = V_{11} A_1 B_1 + V_{32} A_3 B_2^*, \qquad \frac{\partial A_n}{\partial t} = V_{n-1,n-1} A_{n-1} B_{n-1}, \qquad \frac{\partial B_0}{\partial t} = W_1 A_1 A_0^*, \ \frac{\partial B_1}{\partial t} = W_2 A_2 A_1^*, \ \frac{\partial B_{n-1}}{\partial t} = W_n A_n A_{n-1}^*. \quad (9)$$

Here A_k – amplitudes of HF wave; B_k – amplitudes of LF waves; V_{ij}, W_k – matrix elements of nonlinear interaction. The first equation in this set describes dynamics of HF component that has lowest frequency. Right part of this equation contains one addendum only which describes coming of energy in this component from adjacent HF one. Self this component does not decaying. The first terms in the equations for HF waves describe coming energy in these components from neighboring one having higher frequency. The second terms in these equations describe process of decay corresponding component into nearest with lower frequency and corresponding low frequency wave. The last equation for HF components describing highest frequency wave contains one terms only that describes it decay. Right part of equations for low frequency waves contain one addendum only describing energy coming in these components. Numerical analysis of such process show that it may be chaotic. For this amplitudes of interacting wave must be enough large (increment of decay instability must be larger than frequency of LF wave).

2. EXPERIMENTAL RESULTS

Experiment carried out on setup described in [8] together diagnostic tools and methods of investigations of proceeding processes.

In the experiment the magnetic trap as the cylinder with length 100 cm and diameter 16 cm was used. On the it end faces the magnetic field value is large in 1.5…2 times than in central part. Magnetic field in center corresponded to electron cyclotron resonance for frequency oscillations introducing into trap from magnetron. It provided value of introduced power up to 1MW on frequency 2.7…2.8 GHz in the pulse of duration of 1.8 μs. Spectrum of exciting in plasma oscillations and their characteristics was measured with using of oscillography Agilent HP MSO 9404a и Tektronix TDS2022.

Radial and longitudinal ion flows of plasma were measured by disk probe. Energetic spectrum of ions, leaving trap along axis on their outlet, was measured by multigrid analyzer [9]. Preliminary plasma with density up to $10^9…10^{11}$ cm^{-3} was created by electron beams that injected on axis of trap at pressure $(1…5)\times10^{-4}$ Torr. When electromagnetic oscillations with power larger 50 kW is induced in plasma it density increases up to 10^{13} cm^{-3}. Measurement of plasma density was made by double Langmuir probe.

If induced in plasma power exceeded a dozens of kW the excitation of low frequency ion oscillations was observed. This phenomenon is conditioned by modified decay of high frequency waves that discussed in the second section.

Decay appearance of excited HF electromagnetic oscillation is confirmed by availability besides main frequency additional side ones – satellites spaced on frequency of registered LF oscillations. (Fig. 1). This frequency corresponds to Langmuir oscillations of plasma with density of order $\approx 3.0\times10^8$ cm^{-3}.

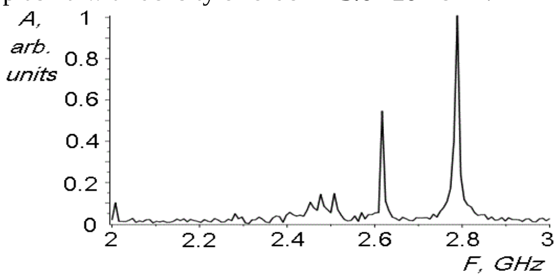

Fig. 1. Spectrum of HF oscillations with power 50 kW induced in plasma on electron cyclotron frequency – 2.77 GHz

In the experiment threshold power of oscillations with frequency ω_1 when appearance of frequencies ω_2 и ω_3 was registered exceeded 50 kW that is in good agreement with theoretical estimation. Low frequency oscillations are wide and stochastic. Spectrum width increases when power of induced HF oscillations increases. As it was shown in experiment at power of HF oscillations large than 50 kW spectrum of LF oscillations may be in the band of 10 kGz up to 100…300 MHz.

On the Fig. 2 the spectrum of low frequency oscillations excited in plasma if induced power exceed 320 kW is presented. As it seen from (see Fig. 2) spectrum spreads up to 300 MHz. Range of low frequency itself includes ion cyclotron frequency $\omega_{hi} \approx 1.0\times10^7$ Hz Hz and low hybrid one $\omega_{lh} \approx 4.0\times10^8$ Hz. Low frequency oscillations may belong to Alfven or fast magnetosound branches. As it follows from expression (6) threshold amplitude of transfer into stochastic regime rapidly decreases with decreasing frequency. It may cause inclusion in the decay process of waves that is in wide range of frequencies. By theoretical estimations in this case ion flows must form.

It was shown by energy measurement of ions on outlet end of trap that at power of HF oscillations in trap of 80 kW ion energy reached 400 eV. At increasing power up to 300 kW ion energy exceeds 1 keV.

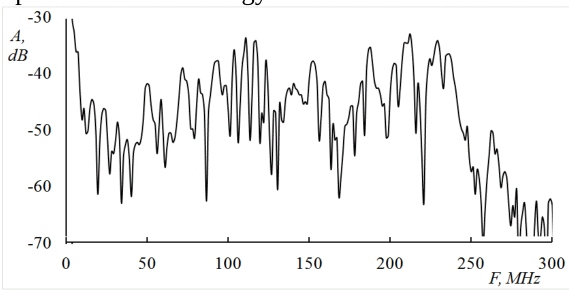

Fig. 2. Spectrum of low frequency oscillations at power of high frequency oscillations of 320 kW on frequency of electron cyclotron resonance

Characteristic is that high energetic ion is formed in plasma during 0.5…1.0 μs from moment of excitation of HF oscillation (Fig. 3). I.e. nonlinear processes of decay generating LF ion oscillations may provide high effective and rapid heating of ions.

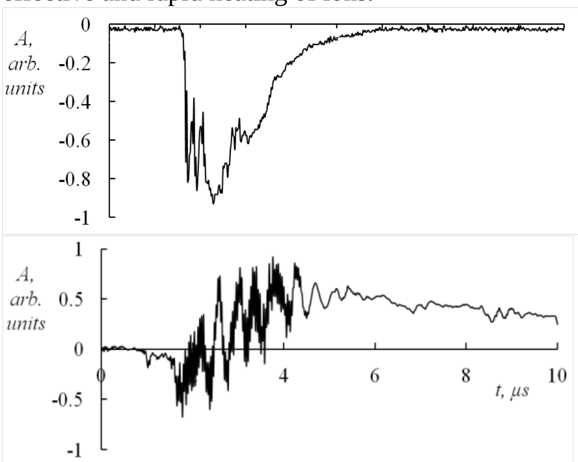

Fig. 3. Time of formation of high energy ion flow(bottom oscillogram) at action HF pulse with power 300 kW (top oscillogram)

CONCLUSIONS

Thus there is enough good qualitatively agreement of theoretical consideration results of energy transformation processes of external electromagnetic wave into energy of waves with low frequency dispersion of which is defined by ion dynamics. Such waves well interact with ion component of plasma and their phase and amplitudes are random function.

It is needed to note that theoretical model which is used in this work describes limited number of physical processes. The first of all we did not took into account interaction processes of type wave–particle. Such processes affect electron component of plasma. So in rare plasma it may study they separately. Besides we took into account only decay with participation of low frequency waves. At the same time decays with participation of Langmuir plasma wave take place.

As it seen on Fig. 1 the red satellite appears which may be considered as HF wave that arise as result of decay with participation of Langmuir wave.

As it seen from formula (5) matrix elements of decay processes are inversely proportional to square of low frequency. So decay processes into LF waves and decays with participation of Langmuir waves may study separately. It is important that criterion of emergence of stochastic instability is inversely proportional to cube of low frequency. So the decay processes with participation of LF wave will transfer to chaos faster than one with participation of Langmuir waves. As result just LF component of excited oscillations first of all becomes no regular. This coincide with results of experiment (see Fig. 2). Taking into account that decay processes into LF plasma oscillations will take place faster than decays with participation of Langmuir waves, and taking into account that excited waves firstly become chaotic, it may expect that appearance of such waves will cause enough fast appearance of energetic particles that interact with this waves. In experiment (see Fig. 3) it is considered enough fast appearance of flow of energetic ions.

LF wave takes part in every process of decay in cascade. So it may expect that it amplitude as result of large number of decays will be larger than in one decay. It may expect that such scenario of decay process is possible when amplitude of LF wave will be maximal.

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ИССЛЕДОВАНИЕ ВОЗМОЖНОСТИ ПЕРЕДАЧИ ЭНЕРГИИ ИОНАМ ПЛАЗМЫ КОЛЕБАНИЯМИ БОЛЬШОЙ АМПЛИТУДЫ НА ЧАСТОТЕ ЭЛЕКТРОННО-ЦИКЛОТРОННОГО РЕЗОНАНСА В МАГНИТНОЙ ЛОВУШКЕ

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Теоретически и экспериментально изучается процесс воздействия мощной поперечной электромагнитной волны на плазму в магнитной ловушке. В теоретической модели учитывается взаимодействие типа волна-волна. Исследование основано на трехволновом взаимодействии. Рассмотрены также каскады трехволнового взаимодействия. В эксперименте изучены спектры волн, возбуждаемых в плазме, и показано достаточно быстрое появление потоков высокоэнергетических ионов. Имеется хорошее качественное согласие теоретических и экспериментальных результатов.

ДОСЛІДЖЕННЯ МОЖЛИВОСТІ ПЕРЕДАЧІ ЕНЕРГІЇ ІОНІВ ПЛАЗМИ КОЛИВАННЯМИ ВЕЛИКОЇ АМПЛІТУДИ НА ЧАСТОТІ ЕЛЕКТРОННО-ЦИКЛОТРОННОГО РЕЗОНАНСУ В МАГНІТНІЙ ПАСТЦІ

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Теоретично та експериментально вивчається процес впливу потужної поперечної електромагнітної хвилі на плазму в магнітній пастці. У теоретичній моделі враховується взаємодія типу хвиля-хвиля. Дослідження ґрунтується на трьоххвильовій взаємодії. Розглянуто також каскади трьоххвильової взаємодії. В експерименті вивчено спектри хвиль, що збуджуються в плазмі, і показано досить швидку появу потоків високоенергетичних іонів. Є гарне якісне узгодження теоретичних та експериментальних результатів.