THE PARAMETRIC EXCITATION OF ION BERNSTEIN MODES AT THE ICR PLASMA HEATING IN THE U-3M TORSATRON

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The results of theoretical and experimental investigations of oscillatory and wave processes at the stellarator plasma edge are presented. Experimental results were interpreted using the kinetic theory of the electron-ion parametrical instability. It is shown that the interaction between plasma and the alternating electric field under conditions carried out in given experiment makes possible a parametric excitation of the ion cyclotron oscillations.

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INTRODUCTION

It is well known that the relative motion of plasma components across the magnetic field lines appears to be a reason of a number of instabilities with a transversal current. If the relative motion velocity is lower or equal to the thermal velocity of ions the frequencies and increments of the mentioned instabilities are in order of ion cyclotron frequency. The reason of such motion of the plasma components presumably lays in the low-frequency electromagnetic wave influence, centrifugal force influence in rotating plasma or strong heterogeneity of plasma density in the transition region between plasma volume and vacuum. If the frequency of the electromagnetic field (pumping wave) is in order of the ion cyclotron frequency the phenomenon acquires a signs of parametrical instability. The theory of ion cyclotron instability of plasma with a transverse current was studied in the great number of works references to which may be found in [1]. The nonlinear theory of the ion cyclotron instability with the transverse current was developed in [2,3]. For the parametric kinetic ion cyclotron instability one could expect that its characteristics are equal to those of the current ion cyclotron instability by the order of magnitude [3].

EXPERIMENTAL SETUP

Experiments were performed on U-3M device. U-3M is a $l = 3$, $m = 9$ torsatron with open helical divertor. The main parameters of plasma and magnetic field are $R = 1$ m, $a = 0.13$ m, $B_0 \leq 1.6$ T, rotational transform $i/2\pi(a) = 0.4$. In this experiment the magnetic field was $B_0 = 0.72$ T. Plasma in U-3M is produced by absorption of RF power ($f = 8 \ldots 8.6$ MHz, $P_{RF} \leq 200$ kW) from 2 antennas placed inside of the helical winding near the last closed magnetic surface. Frame aerials are used to excite the RF wave in plasma.

DIAGNOSTIC ELEMENTS

A set of capacitive probes (3 probes) was used as the signal detectors. The probes were placed at the periphery of the confinement volume Fig.1. The signals from each of detectors were transmitted by the microwave coaxial cable to the spectrum analyzer. A constant bias voltage was applied on the probes through the same coaxial lines using a stabilized voltage source. The magnitudes of plasma density and temperature on the periphery of the confining volume were obtained using a microwave diagnostics and probe measurements. The density in the probe area was determined using an X-wave interferometry [4].

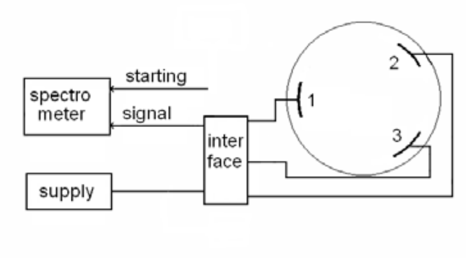

Fig.1. The scheme of experimental measurements

EXPERIMENTAL RESULTS

The results of experimental study of the oscillatory processes observed at the edge of plasma confined in U-3M torsatron are presented here. The plasma was created by the RF discharge with the frequencies located near the ion cyclotron resonance. To study the nature of observed oscillations a number of spectrograms were obtained.

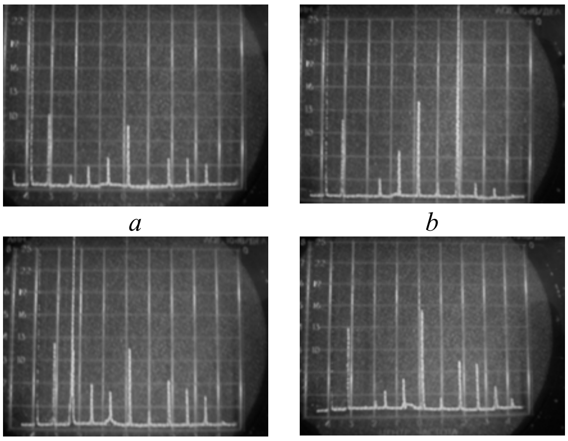
a *b* *c* *d*

Fig.2. The dynamics of oscillations spectra for different values of RF pumping power (H =7 kOe, Δt =12…22 ms): a) U= 5kV, b) U=6 kV, c) U=7 kV, d) U=8 kV

The measurements were carried out with the different magnitudes of the RF power introduced into the plasma volume (Fig. 2), magnitudes and polarities of potential applied to the diagnostic probes (Fig. 3), time intervals constituent to the RF pumping pulse (Fig. 4). To consider the spatial dynamics of the oscillations spectrum a comparison of signals obtained from different spatially separated probes was made. The oscillations spectrum was analyzed right up to the ninth harmonic component of the ion cyclotron frequency.

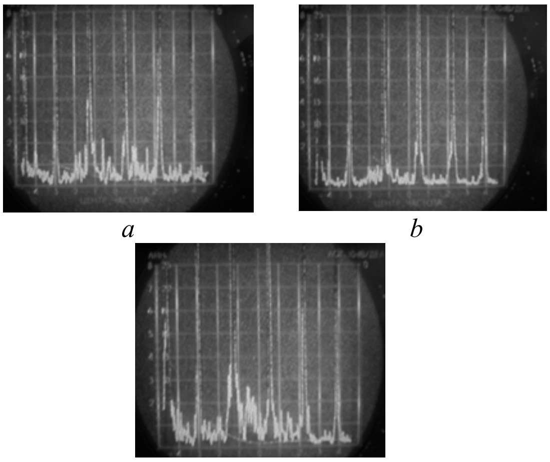
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Fig.3. The probe potential magnitude and polarity influence on the oscillations spectrum (H = 7 kOe, Δt =12…22 ms, U_A = 8 kV): a) U_{PR} = 0 V, b) U_{PR} = +200V, c) U_{PR} = -200 V

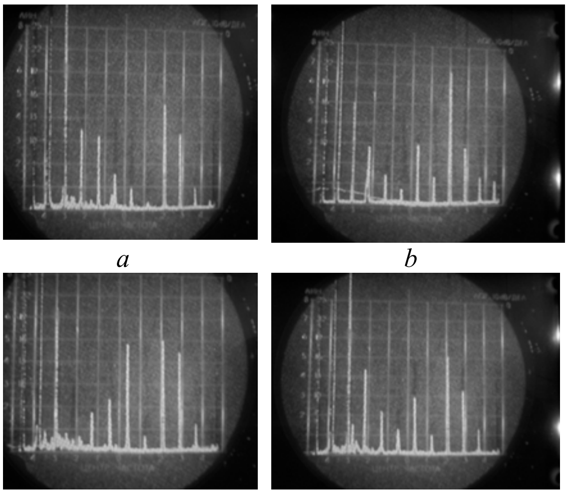
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Fig.4. The dynamics of oscillations spectra for different temporal zones of RF pumping pulse (H = 7 kOe, U_A = 8 kV): a) Δt = 0…12 ms, b) Δt = 12…22 ms, c) Δt = 22…32 ms, d) Δt = 32…42 ms

THEORETICAL ESTIMATES AND NUMERICAL SIMULATION

Comparison of the results of the linear analysis of parametric electron-ion instability with the obtained from numerical simulation spectral characteristics and experimental data allows us to perform frequencies identification and shows that the oscillation frequencies, derived from the linear dispersion equation, predominate in the numerical and experimental spectra, where maximums of the intensity correspond to them.

The numerical solution of the linear parametric dispersion equation is depicted in Fig. 5. This dispersion equation is derived from the solvability condition for the system of difference equations [5]

$$\left[1+\delta\varepsilon_i(\omega)\right]\eta(\omega)+\sum_{n,m=-\infty}^{\infty}J_n(a_E)J_{n+m}(a_E)\times \\ \times\delta\varepsilon_e(\omega+m\omega_0)\eta(\omega-n\omega_0)=Q(\omega), \qquad (1)$$

where $\delta\varepsilon_e$ and $\delta\varepsilon_i$ are the contributions of electrons and ions to the plasma permittivity, J_n are Bessel functions, a_E is the relative displacement of electrons in the field of the pumping wave. Equating of the infinite determinant of the system (1) to zero gives

$$\det\left|A_{mn}\right|=0\,, \qquad (2)$$

where the matrix elements appear as follows

$$A_{mn}=\delta_{mn}+\frac{1}{1+\delta\varepsilon_e(\omega+m\omega_0)}\sum_{\alpha}\sum_{p=-\infty}^{\infty}J_{p+m}(a_\alpha)J_{p+n}(a_\alpha)\times \\ \times\delta\varepsilon_e(\omega+p\omega_0).$$

The case of the strong non-isothermal plasma, $T_e=10\cdot T_i$, are presented in Fig. 5 for the pumping field frequency ω_0=0.8$\,\omega_{ci}$. The oscillations frequency and growth rate dependencies against the transverse wave number are shown in the instability regions. We note that two instability regions exist: the short-wavelength region with $k\rho_i\geq 1$ (Fig. 5) and the more long-wavelength region with $k\rho_i<1$, (not shown here). It is clear that the spectrum of Bernstein modes considerably varies due to particles oscillations in the pumping wave filed. Splitting of each Bernstein mode occurs on two branches with the same growth rate. Near the splitting point oscillations become unstable and have maximum growth rate $\gamma/\omega_{ci}\approx 1.5\cdot 10^{-3}$.

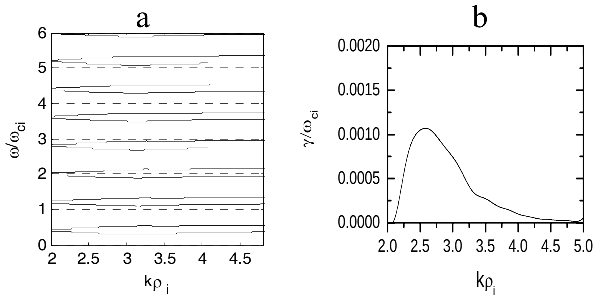

Fig.5. Frequency (a) and growth rate (b) against the transversal wave number with T_e/T_i =10 ($k_{\|}\rho_i$ =0.003)

Numerical simulation of ion cyclotron parametric instability is curried out using the code based on macro particles technique [6]. For the computations the numerical parameters, which correspond to the experimental parameters, were chosen: plasma density n=3·10^{10} cm^{-3}; magnetic field B_0=7 kG; E_0=1.5 V/cm, pumping wave frequency f_0=9 MHz, antenna size L_a=40 cm, electron temperature T_e=30 eV. It is assumed that at the plasma boundary ion temperature is considerably less than electron temperature T_i=0.1T_e. At that the relation of the pumping field frequency to the ion cyclotron one is equal to ω_0/ω_{ci} =0.8, and the relation of the electron plasma frequency to the electron cyclotron one comes to ω_{pe}/ω_{ce} =0.09, i.e. electrons are strongly magnetized. The initial particles distribution over velocities is maxwellian one and it is uniform in the space. The numerical simulation results show that in this case the weak parametric instability appears with not large growth rate $\gamma/\omega_{ci} \approx 0.0012$. The electric field energy slow increases and becomes saturated at the level which agrees with the estimate (1). Comparison of the frequency spectrum of the most unstable mode ($k_{\perp}\rho_i$ =0.9, $k_{\|}\rho_i$ =0.003) with the experimental one for the input power 7 kV reveals that they are similar. It follows from Fig. 6, which is obtained by superposition of the numerical simulation spectrum (white color) and the experimental one (in black). A difference appears beginning with the fifth harmonic which amplitude disproportionately decreases in the numerical simulation.

Development of the instability results in unsubstantial growth of the longitudinal electron temperature (about 2%) and the transversal ion temperature. At the same time the longitudinal ion temperature remains at the initial level. It agrees well with the theoretical estimate (2).

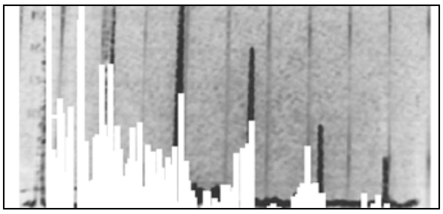

Fig. 6. Comparison of the experimental spectrum (in black) and the spectrum of the most unstable mode (in white)

CONCLUSIONS

The oscillations spectrum form changing is closely connected with the pumping power increasing. Higher harmonics become more pronounced. The appearance of additional spectral components near the primary harmonics may be considered as a threshold phenomenon. The appearance of a higher harmonics corresponds to the plasma density increasing. The results of numerous experiments have shown the possibility of ion and electron contributions separation by applying a bias voltage on the measuring probe. The behavior of ion spectral component differed from those of electron component. The numerical simulation of the electron-ion parametric instability shows the following. The frequency spectra of the ion cyclotron oscillations considerably vary even when amplitude of the oscillation velocity of the electrons with regard to the ions is less than the ion thermal velocity. In the instability region the ion Bernstein modes break up into two branches. Maximum value of the growth rate is about $1.5\cdot10^{-3}\cdot\omega_{ci}$. Computed values of the frequencies and the growth rates qualitatively agree with the analytical results. For the electron-ion parametric instability the level of the oscillations at the quasi-stationary stage corresponds well to the estimate (2) which was derived in [3] from the condition of the instability saturation due to the nonlinear broadening of the cyclotron resonances. Obtained with the numerical simulation frequency spectra conform to the experimental data. It allows to think that in the experiment the electron-ion parametric instability occurred. It conditions the character of the obtained experimental spectra.

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ПАРАМЕТРИЧЕСКОЕ ВОЗБУЖДЕНИЕ ИОННЫХ БЕРШТЕЙНОВСКИХ МОД ПРИ ИЦР- НАГРЕВЕ ПЛАЗМЫ В ТОРСАТРОНЕ У-3М

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Представлены результаты теоретических и экспериментальных исследований колебательных и волновых процессов в периферийной стеллараторной плазме. Экспериментальные результаты интерпретируются на основе кинетической теории электрон-ионной параметрической неустойчивости. Показано, что воздействие переменного электрического поля на плазму в условиях данного эксперимента делает возможным параметрическое возбуждение ионных циклотронных колебаний.

ПАРАМЕТРИЧНЕ ЗБУДЖЕННЯ ІОННИХ БЕРНШТЕЙНІВСЬКИХ МОД ПРИ ІЦР- НАГРІВАННІ ПЛАЗМИ В ТОРСАТРОНІ У-3М

В.В. Ольшанський, К.М. Степанов, І.К. Тарасов, М.І. Тарасов, Д.А. Ситников, А.І. Скибенко, Є.Д. Волков

Представлені результати теоретичних та експериментальних досліджень осциляторних й хвильових процесів в периферійній стелараторній плазмі. Експериментальні результати інтерпретуються на основі кінетичної теорії електрон-іонної параметричної нестійкості. Показано, що дія змінного електричного поля на плазму в умовах даного експерименту робить можливим параметричне збудження іонних циклотронних коливань.