RELATIONSHIP OF ION BERSTEIN WAVES INDUCED BY HIGH-POWER HF FIELDS TO PLASMA PARAMETERS ON AN URAGAN-3M TORSATRON

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On a U-3M torsatron at the RF power heating, narrow spectral band plasma density oscillations were observed near the harmonics of ion cyclotron frequencies. The estimation of wave numbers showed that the condition for the excitation of short wavelength ion Bernstein modes is fulfilled. The observed correlation of the ion temperature with the spectral width of harmonics possibly illustrates the role of excited oscillations for the ion heating process.

1. Introduction

In a U-3M torsatron, a currentless plasma is produced and heated by the absorption of power from Alfven waves ($f_a \approx (0.7 \div 0.9) f_{ci}$) excited in plasma by RF antennas. Two different frame-type antennas allowing the gas breakdown, plasma build-up, and heating have been used in recent years [1]. The heating of electrons and ions under experimental conditions was observed: $P_{\rm RF} \approx 200$ kW, $T_e(0) \leq 500$ eV, $T_i \leq 350$ eV, and $n_e(0) \leq 2 \times 10^{18}$ m^{-3}.

The study of the plasma heating using the RF power absorption on an Uragan-3M torsatron showed that the achieved ion temperature cannot be explained by the Cherenkov and ion-cyclotron absorption of the wave energy. It was natural to investigate other processes which are able to provide the ion heating. The conditions of the excitation of plasma oscillations near the ion cyclotron frequency under influence of RF fields, which can transfer the energy to ions, were studied in many theoretical works [3–11].

The qualitative explanation of the heating of electrons and ions in plasma by the AW RF power absorption in U-3m has been given in work [11]. In that work, the excitation of both the fast (electromagnetic) and slow (kinetic Alfven) waves and the effects of their mutual conversion have been studied numerically. The linear mechanisms of electron Cherenkov and ion cyclotron absorptions have been taken into account.

The calculations have shown the amplitudes of excited waves to be high enough so the relative velocity of electrons and ions $u = |\vec{v}_e - \vec{v}_i|$ becomes comparable with the ion thermal velocity V_{T_i}. In this case, the short wavelength ion Bernstein waves can be excited ($k\rho_{{\rm L}_i} \sim V_{T_i}/u \sim 3$) with the frequencies $\omega(k) \approx n\omega_{ci}$ and the growth rates $\gamma \sim \omega_{ci} u/V_{T_i}$, ($\rho_{{\rm L}_i}$ is the ion Larmor radius) [11].

At the nonlinear stage, the saturation of these instabilities occurs due to the nonlinear broadening of the cyclotron resonance because of the random walk of ions in the field of unstable IBW's at the level $w/nT_e \sim (u/V_{T_i})^4$, ($T_e > T_i$). The scattering of ions on turbulent fluctuations increases their "transverse" temperature [10].

This work is devoted to the search for a manifestation of ion Bernstein waves predicted in [11] with $\omega(k) \approx n\omega_{ci}$ and $k\rho_{{\rm L}_i} \approx 3$. Such waves with $n = 1,2,3$ and $k\rho_{{\rm L}_i} \approx 1-3$ manifested as plasma density fluctuations have been observed by the backscattering of microwaves.

The spectral properties of plasma density fluctuations obtained from microwaves reflectometry have been studied. The search for oscillations with frequencies corresponding to harmonics of the ion cyclotron frequency predicted in [11] has been fulfilled. The observation of the relationship between the characteristics of spectral maxima at the frequencies of ion Bernstein waves and the plasma parameters was of the particular interest.

2. Experiment

Experiments were performed on a U-3M device which is an $l = 3$, $m = 9$ torsatron with open helical divertor [1,2]. Main parameters of plasma are $R = 1$ m, $a = 0.13$ m, the magnetic field was $B_0 = 0.72$ T in this experiment, and the rotational transform $\iota/2\pi(a) = 0.4$. Plasma in a U-3M is produced by the absorption of RF power ($f =$

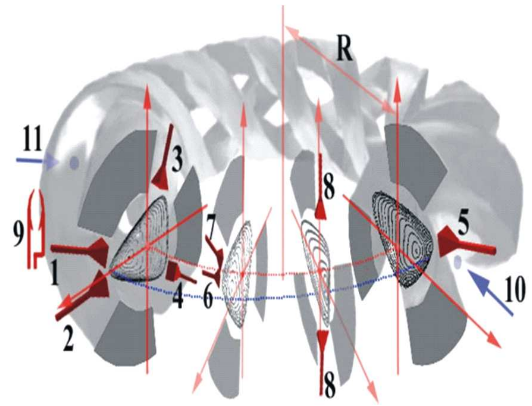

Fig. 1. The location of microwave diagnostics at an "Uragan-3M" torsatron: antennas *1–7* – were used for the reflectometry, antenna *8* – was used for the interferometry, *9* – Fabry–Perot resonator, RF power put in plasma by antennas *10, 11*

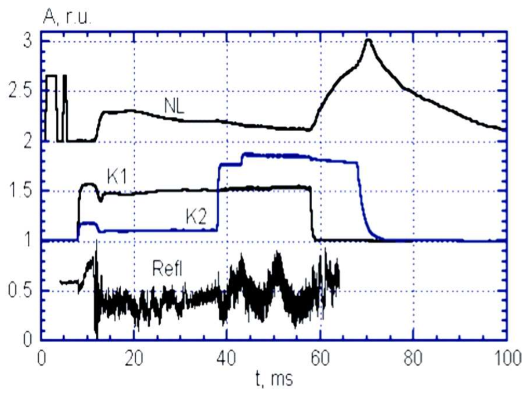

Fig. 2. Time traces of the integral density NL, HF current of the 1-st ($K1$) and 2-nd ($K2$) oscillators, and a reflected microwave signal

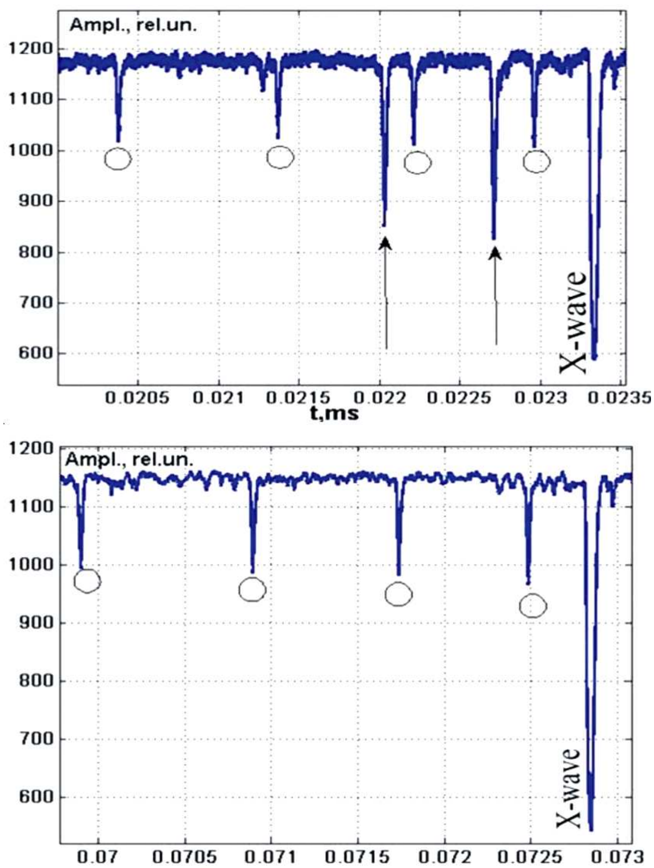

Fig. 3. Traces of the spectroanalyzer output during one modulation period at the outward probing; during a RF pulse (upper) and after a RF pulse (lower). Frequency marks ($\Delta f = 10$ MHz) are labeled by circles

8÷8.6 MHz, $P_{\rm RF} \leq 200$ KW) from 2 antennas put inside a helical winding near the last closed magnetic surface. The frame-type antennas are used to excite RF waves in plasma.

The location of the microwave diagnostics on a torsatron "Uragan-3M" is shown in Fig. 1. The electron density averaged over the central chord was measured by a 2-mm interferometer, divertor flows were measured by a Fabry–Perot resonator, central electron temperature was measured by ECE (on the second harmonic of ECR), and the ion temperature was measured by an energy analyzer of charge exchange neutrals.

Typical time traces of the plasma integral density NL, HF current of the 1-st ($K1$) and 2-nd ($K2$) oscillators, and a reflected microwave signal are shown in Fig. 2.

Microwave reflectometry was the main tool for the studies of plasma density fluctuations [13].

Backscattering of microwaves was observed in one cross-section (D-D) of device, where 3 horn antennas were installed. Antenna *2* was used for the X-wave outward ($F = 19 \div 21$ GHz) and antenna *4* – for the O-wave inward ($F = 11 \div 13$ GHz) probing and the backscattered microwave observation. Under the experiment condition ($n_e(r)_{\max} \leq 4 \times 10^{18}$ m^{-3}), the used microwaves allowed us to observe the reflection from almost all outer and inner plasma radii. A superheterodyne receiver with a saw-tooth modulation of the frequency ($\Delta F = 0 \div 60$ MHz, modulation frequency – 250 Hz) was used for direct observations of the spectrum of phase modulated backscattered microwave signals.

Typical expanded traces of the spectroanalyzer output (during one modulation period) are shown in

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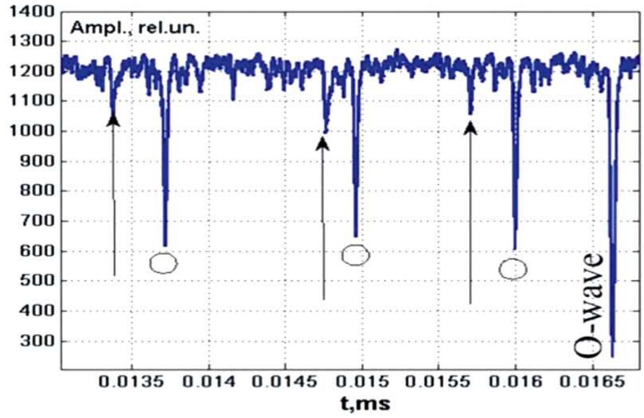

Fig. 4. Trace of the spectroanalyzer output during one modulation period at the inward probing

Figs. 3 and 4. Two clear satellites of a probing signal (arrows) with the frequency difference of ∼9 MHz are observed at the outward X-wave probing ($F = 19$ GHz) (Fig. 3), and 3 satellites with smaller amplitudes have been observed at the inward O-wave probing ($F = 11.5$ GHz) (Fig. 4). These satellites were observed only during a RF pulse.

One can see that the observed satellites in spectra correspond to harmonics of the ion cyclotron frequency. A cut-off layer position for a probing frequency was calculated from reflected wave phase shift measurements, the ion cyclotron frequencies f_{ic} were obtained from the results of calculations of the vacuum magnetic field, and ion Bernstein waves frequencies $f_{\rm IBW}$ were measured. The results of the comparison are presented in Table 1, where R is the big radius of a torsatron.

The comparison of the observed frequencies IBW at the outward probing ($0.59T < B < 0.66T$) and at the inward probing ($0.66T < B < 0.8T$) is shown in Fig. 5. All values of IBW frequencies correspond to $f < 10.1$ MHz if they were measured at the outward probing and to $f > 10.1$ MHz at the inward probing (the ion gyrofrequence is 10.1 MHz near the magnetic axis), as shown in Fig. 5. Similar calculations for other shots showed that the frequency of observed harmonics divided by the harmonic number coincides with calculated values of the ion cyclotron (IC) frequency within near 10%.

T a b l e 1

t, ms	$f_{\rm IBW}$	R, cm	$f_{\rm calc}$
14	9.3	109	9.4
20	9.6	108	9.6
30	9.75	108	9.6
40	9.8	107.5	9.7

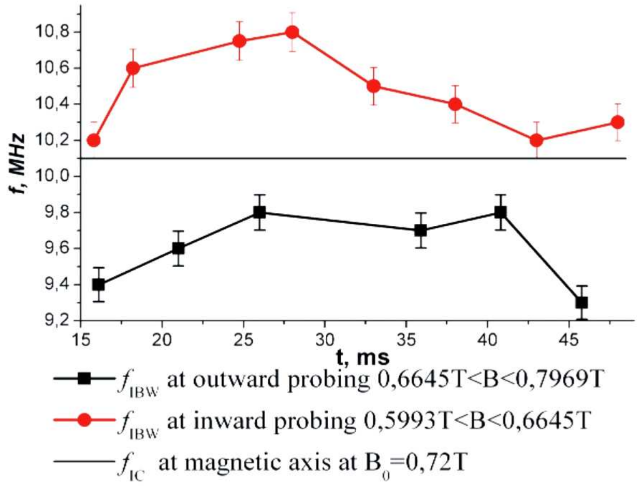

Fig. 5. Time dependences of the observed frequency at outward and inward probings

Besides of the frequency spectrum of observed fluctuations, we estimated the “radial” component of the fluctuation wave vector $\mathbf{k}_f$. The simplest estimate of $\mathbf{k}_f$ follows from

$$\bar{k}_{\rm ref} = \mathbf{k}_{\rm incid} + \mathbf{k}_f, \tag{1}$$

where $\mathbf{k}_{\rm ref}$ and $\mathbf{k}_{\rm incid}$ are the $\mathbf{k}$ vectors of reflected and incident microwaves. For microwave backscattering, the fluctuation wave vector modulus is

$$|k_f| = 2|k_{\rm incid}|. \tag{2}$$

A more accurate estimate of $\mathbf{k}_f$ is given in [14],

$$1.26 \times k_{\rm incid}^{2/3} L^{-1/3} < k_f < 2k_{\rm incid}, \tag{3}$$

where $L = \frac{n}{\nabla n}$, and n is the plasma density. Under the experiment conditions ($n_{0\,\rm max} = 4 \times 10^{18}$ m^{-3}), a range of $k_{\rm incid}$ was 3.5–6 cm^{-1} and 2–4 cm^{-1} for outward and inward probings, respectively. Thus, the range of $\mathbf{k}_f$ coming from (1) is 3 cm^{-1} $< \mathbf{k}_f <$ 12 cm^{-1} and range of $k_f\rho_{{\rm L}_i}$ is $0.5 < k_f\rho_{{\rm L}_i} < 3$ (for $T_i = 250$ eV). It is worth to note that the upper limit for the observed $\mathbf{k}_f$ was determined by the plasma density/cut-off /probing frequency range in experiment.

The X-wave reflection takes place in the density layer of the lower cut-off $N(r) = N_c(1 - f_{ce}/f)$ or in the layer of the upper hybrid resonance (UHR) $N(r) = N_c[(1 - f_{ce}/f)^2]$, where f and f_{ce} are probing and electron cyclotron frequencies, and N_c is the cut-off density for f. The first layer takes place nearly to the plasma edge. But, on the second layer, the condition is

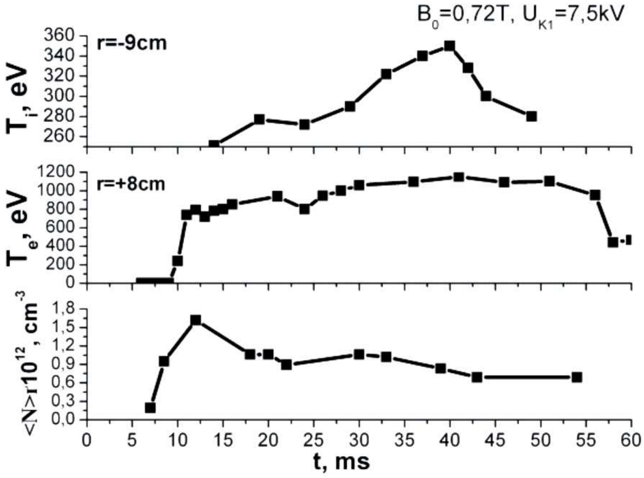

Fig. 6. Time behavior of T_e and T_i and NL during the IBW observation

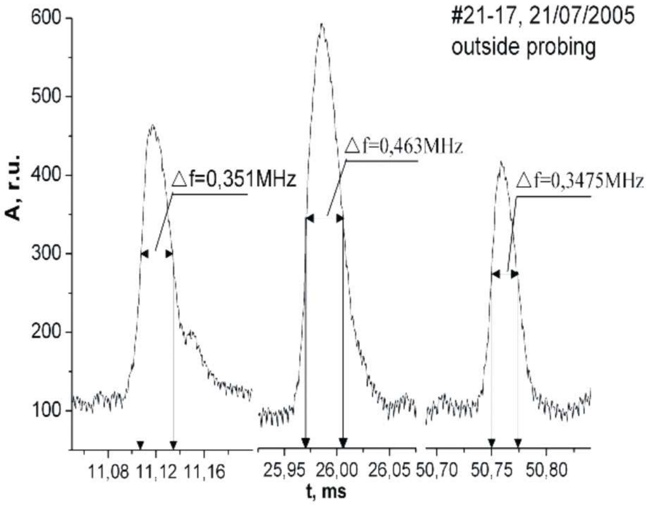

Fig. 7. Change of the halfwidth and the amplitude of the 1st harmonic during a discharge at the outward probing by an X-wave ($f = 19$ GHz)

fulfilled better for the extraordinary wave backscattering by small-scale plasma fluctuations. The calculations were fulfilled for both cases. The values of the cut-off radius, local density, and ion gyrofrequency are evaluated for both layers from the equations

$$N_0[1-(r/a)^m] = N_c(1-f_{ce}(B(r))/f), \quad (4)$$

$$N_0[1-(r/a)^m] = N_c[1-(f_{ce}(B(r))/f)^2], \quad (5)$$

respectively. The results of these calculations showed that the local density and the ion gyrofrequency nearly coincide with the measured values (Table 2) if the condition of UHR is fulfilled, where $f^{(1)}_{\rm cal}$, $f^{(2)}_{\rm cal}$, $N^{(1)}_c$, and $N^{(2)}_c$ are the frequencies and densities calculated for two cut-off cases.

Under the conditions that the enhanced scattering on UHR is realized if the fluctuations possess wavelengths smaller than the half probing wavelength [15], the wave number $k \leq 9$ cm^{-1}. Taking into account that $\rho_i \approx 0.2 \div 0.3$ cm and $k\rho_i \approx 3$, the condition for the excitation of a short wavelength ion Bernstein wave is fulfilled.

Although the phase beating amplitude is not related directly to the amplitude of density fluctuations [13], some additional information can be obtained from the widths of harmonics. If the level of density fluctuations is small, $\frac{\delta n}{n} \ll 1$, the halfwidth of observed pulses in spectra is proportional to that of electron density fluctuations.

Studying the evolution of IBW harmonics at a change of the plasma parameters was carried out for N_e and T_e which are presented in Fig. 6. The $T_e(t)$ dependence was determined by radiation with $f = 36.5$ GHz that corresponds to a distance of 3.6 cm from the magnetic axis or 8 cm from the geometric axis at the outward side of the torus at $B_0 = 0.72$ T, $U_{k1} = 7.5$ kV, and $U_{k2} = 8$ kV.

Under these conditions, the change of the halfwidth and the amplitude of the 1st harmonic studied during the time evolution of plasma parameters in a discharge at the X-wave probing ($f = 19$ GHz) (Fig. 7) and at the inward O-wave probing ($F = 11.5$ GHz, $n_c = 1.72\times10^{12}$ cm^{-3}) (Fig. 8).

Temporal dependences of the spectral halfwidth of the 1st harmonic at different locations of a reflecting layer at the outward probing with X-waves are presented in Fig. 9 ($f = 21$ GHz at the top, and $f = 19$ GHz below). The reflection at a less frequency takes place in a more external layer according to the equation

$$N_c(1-\frac{f_{ce}(r)}{f}) = \bar{N}\frac{p+1}{p}\Big[1-\Big(\frac{r_{\rm ref}}{a}\Big)^p\Big], \quad (6)$$

where $\overline{N}$ and N_c are, respectively, the average density and the density cut-off, $r_{\rm refl}$ is the position of a reflecting layer at a probing frequency f, and p is the power index.

The comparison of the spectral halfwidth of the 1st and 2nd harmonics at the outward probing ($f = 19$ GHz) during a discharge is presented in Fig. 10.

T a b l e 2

$f_{\rm prob}$, GHz	Frequency of fluctuations, MHz			Local density, 10^{12} cm^{-3}	
	$f_{\rm measured}$	$f^{(1)}_{\rm cal}$	$f^{(2)}_{\rm cal}$	$N^{(1)}_c$	$N^{(2)}_c$
19	9.6	9.55	9.37	0.64	0.40
20	9.7	9.73	9.5	0.98	0.62
21	10.0	9.93	9.65	1.3	0.85

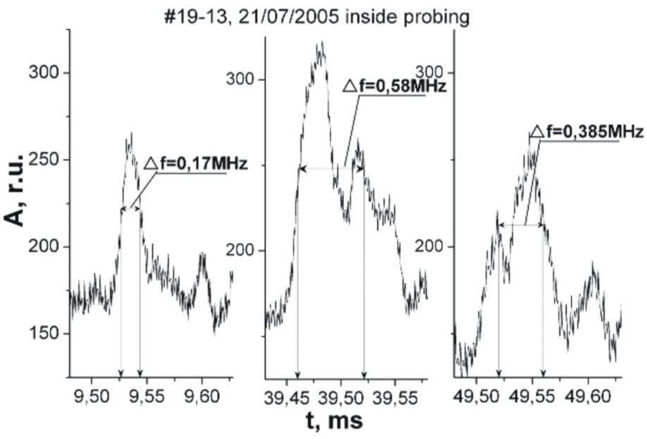

Fig. 8. Change of the halfwidth and amplitude of the 1st harmonic during a discharge at the inward probing by an O-wave (f = 11.5 GHz)

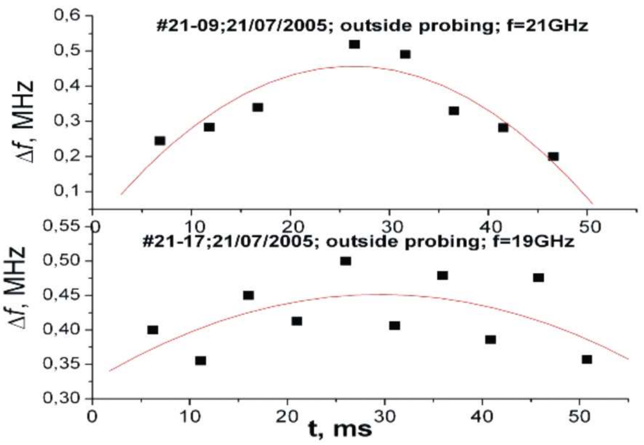

Fig. 9. Time dependences of the spectral halfwidth of the 1^{st}harmonics for two different locations of reflecting layers

At the inward probing, the widths of the (1st, 2nd, and 3d) harmonics changed during a discharge (Fig. 11): the largest spectral width was observed on the 3d maxima, when the ion temperature achieved the maximum value.

The study and comparison of the evolutions of the spectral halfwidth of the first harmonic and the ion temperature are of a special interest. They are presented in Fig. 12 together with the radial dependence of a reflecting plasma layer. The local temperature was measured for two plasma layers. The maxima of the temperature and the width are observed on the external half of the plasma radius.

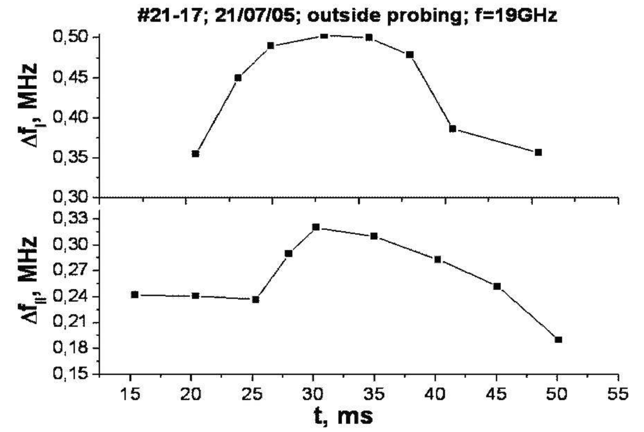

Fig. 10. Comparison of the spectral halfwidth of the 1st and 2nd harmonics

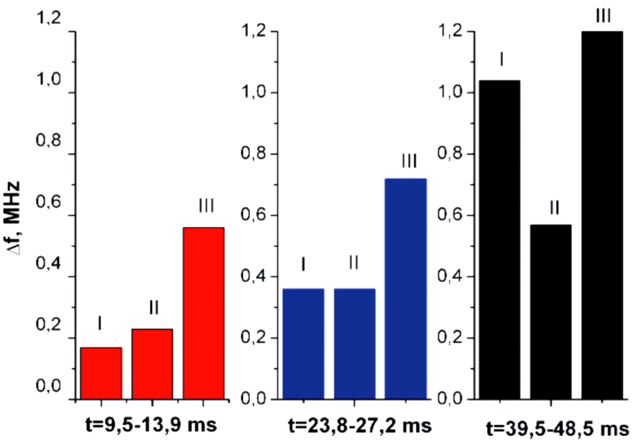

Fig. 11. Time change of the 1st, 2nd, and 3d harmonics at the inward probing during a discharge

3. Conclusion

In a U-3M torsatron at the RF power heating, the narrow spectral band plasma density oscillations were observed near harmonics of ion-cyclotron frequencies, which can be identified as short-wave ion Bernstein modes.

All values of these modes change at a reflecting layer displacement in correspondence with the radial distribution of a magnetic field in the plasma trap. The change of the spectral halfwidth of IBW harmonics coincides with the evolution of the ion temperature during a discharge. The observed correlation of the ion temperature with the spectral width of harmonics possibly illustrates the role of excited oscillations for the ion heating process.

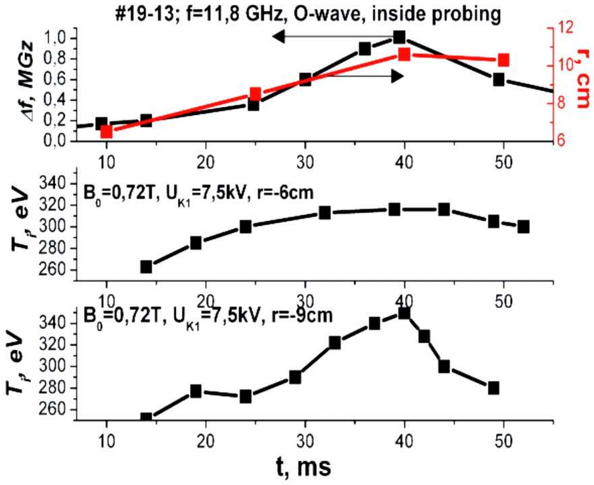

Fig. 12. Comparison of the evolutions of the halfwidth of the 1st harmonic, reflecting layer radius (above), and ion temperature at $r = 6$ cm (in the middle) and at $r = 9$ cm (below)

The properties of the observed phenomena are similar to those predicted by the theory [11] of the scattering of ions by turbulent fluctuations and the turbulent heating.

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ЗВ'ЯЗОК ХАРАКТЕРИСТИК ІОННИХ ХВИЛЬ БЕРНШТЕЙНА, ЗБУДЖУВАНИХ ПОТУЖНИМИ ВЧ-ПОЛЯМИ, З ПАРАМЕТРАМИ ПЛАЗМИ ТОРСАТРОНА "УРАГАН-3М"

А.І. Скибенко, О.С. Павліченко, О.В. Прокопенко, І.К. Тарасов, В.Л. Бережний, А.Є. Кулага, О.С. Славний

Р е з ю м е

У торсатроні "Ураган-3М" у процесі ВЧ-нагрівання спостерігали флуктуації густини плазми у вузькій смузі частот поблизу гармонік іонних циклотронних частот. Оцінки хвильових чисел показали, що виконуються умови для збудження короткохвильових мод Бернштейна. Спостережувана кореляція іонної температури зі спектральною шириною гармонік ІХБ, можливо, ілюструє роль збуджуваних коливань в процесах нагрівання іонів.