EXCITATION OF PLASMA FLUCTUATIONS NEAR ION GIROFREQUENCIES DURING RF PLASMA HEATING IN URAGAN-3M TORSATRON

A.I. Skibenko, O.S. Pavlichenko, V.L. Berezhnyj, P.Ya. Burchenko, A.E. Kulaga,
V.L. Ocheretenko, I.B. Pinos, A.V. Prokopenko, A.S. Slavnyj, I.K. Tarasov, O.Yu. Volkova

Institute of Plasma Physics, NSC "Kharkov Institute of Physics and Technology",
61108, Akademicheskaya Str. 1, Kharkov, Ukraine

Curentless plasma in Uragan-3M (U-3M) is produced and heated by absorption of RF power in the region of Alfven waves (AW) [1]. The process of plasma heating was explained in [2] as a result of Cherenkov absorption of energy of the fast (EM) and slow (kinetic Alfven) waves by electrons and turbulent ion heating due to excitation of short wave ion Bernstein waves (IBW). In this report we present results of studies of plasma density fluctuations showing existence of a narrow bands near the frequencies of $\omega \approx n\omega_{ci}$ (n = 1, 2, 3).

PACS: 52.55.Hc

1. INTRODUCTION

In U-3M torsatron curentless plasma is produced and heated by absorption of power from Alfven ($\omega \approx 0.7 \div 0.8 \cdot \omega_{ci}$) waves excited in plasma by RF antennae. Two different frame type antennas allowing gas breakdown, plasma build-up and heating has been used in recent years. Both electron and ion heating for experiment condition were observed ($P_{RF} \approx 200$ kW, $T_e(0) \leq 500$ eV, $T_i \leq 350$ eV, $n_e(0) \leq 2 \cdot 10^{18}$ m^{-3}).

The qualitative explanation of both electron and ion heating of plasma by AW RF power absorption in U-3m has been given in paper [2]. In this 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 the electron Cherenkov and ion cyclotron absorption have been taken into account. The ion cyclotron absorption of RF power was negligible.

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

At the nonlinear stage the saturation of these instabilities occurs due to the nonlinear broadening of 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 [4].

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

2. EXPERIMENT

Experiments were performed on U-3M device. U-3M device is a l= 3, m = 9 torsatron with open helical divertor [1,5]. Main parameters of plasma are R = 1 m, a = 0.13 m, rotational transform $\iota/2\pi(a) = 0.4$. In this experiment magnetic field was B_0 = (0.65…0.72)T. Plasma in U-3M is produced by absorption of RF power (f = 8…8,8 MHz, $P_{RF} \leq 200$ KW) from 2 antennas put inside of helical winding near the last closed magnetic surface. Frame type antennas are used to excite RF waves in plasma.

Typical parameters were measured during RF impulse: central chord averaged electron density by 2 mm interferometer, radial density profile by UHF reflectometry ($n(r) = (0.3…3) \cdot 10^{12}$ cm^{-3}), radial electron temperature profile by ECE ($T_e(r)$ = 40…600 eV), perpendicular ion energy distribution was determined by CX neutral mass-energy analyser and cosists of two temperature groups $T_{i1} \approx 50$ eV and $T_{i2} = 250 \div 400$ eV.

Backscattering of microwaves was observed in one crossection (D-D) of device where 3 horn antennas were installed (Fig.1) [6]. Antenna 1 was used for X-wave outward (F = 19…21 GHz) and antenna 3 – for O-wave inward (F = 10…12 GHz) probing and backscattered microwave observation. For experiment condition ($n_e(r)_{\max} \leq 4 \cdot 10^{18} m^{-3}$) used microwaves allowed to observe reflection from almost all outer and inner plasma radius. The superheterodyne receiver with saw-tooth modulation of frequency ($\Delta F = 0 \div 60$ MHz, modulation frequency – 250 Hz) was used for direct observation of spectrum of backscattered microwave signals. Typical trace fragments of spectroanalyser output are shown on

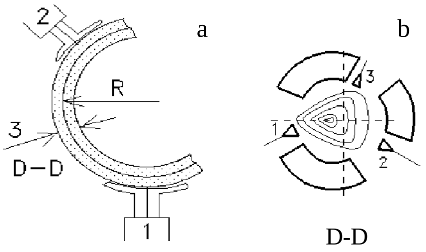

Fig.1. Schematic view of RF and microwave antennas location on U-3M torsatron

Fig.2 (outward probing at X-wave) and on Fig.3 (inward O-wave probing). On figures frequency marks ($\Delta f = 10$ MHz), probing frequency and IBW maxima are labeled by circles, squares and arrows respectively.

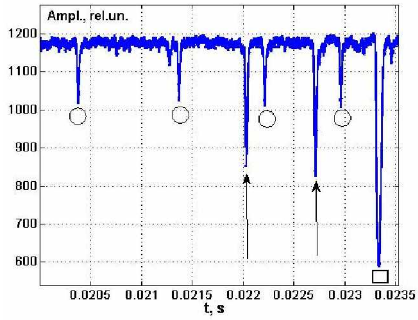

Fig.2. Signals of spectroanalyser; expanded traces – during RF pulse (upper) and after RF pulse (lower). Frequency marks ($\Delta f = 10$ MHz) are labeled by circles

Two clear maxima with the frequency difference of ~ 9 MHz are observed at outward probing (F = 19 GHz).

At inward O-wave probing (F = 11.5 GHz) 3 maxima with smaller amplitude has been observed (Fig.3).

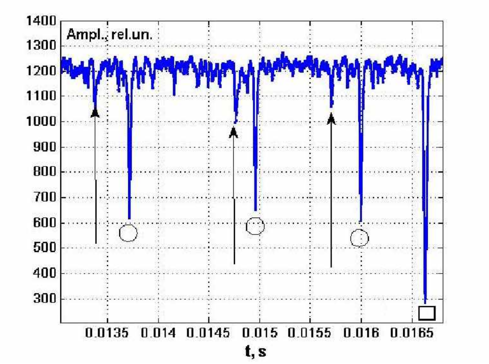

Fig.3

Comparison of measured frequencies of observed maxima in spectra with ion cyclotron frequency at cut-off layer was produced as follows. A cut-off layer position for a probing frequency was calculated from phase shift measurements (Fig.4).

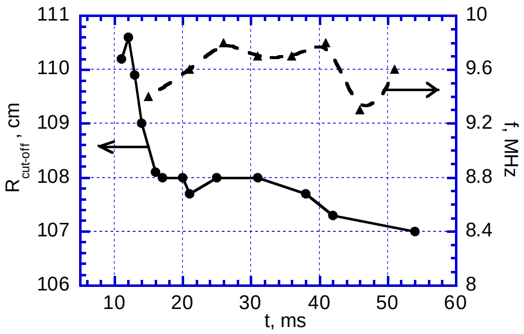

Fig.4

Time behavior of first maximum of spectra for a discharge where cut-off layer position was measured is shown on Fig.4.

A predicted value of ion cyclotron frequency was obtained from data of vacuum magnetic field calculation (Fig.5).

The calculated value for ion cyclotron frequency for cut-off layer position $R_{cut-off} = 107$ cm is $f_{ci} \approx 9.8$ MHz and is near to value of frequency of first maximum shown on Fig.4. Similar calculations for other shots showed that frequency of observed maxima divided by harmonic number coincide with calculated values of ion cyclotron (IC) frequency within of 10-15% (Fig.5).

Time behavior of IC harmonic amplitudes is shown for outward and inward parts of plasma column (Fig.6-7). They observed during whole plasma discharge duration but their time behavior was different.

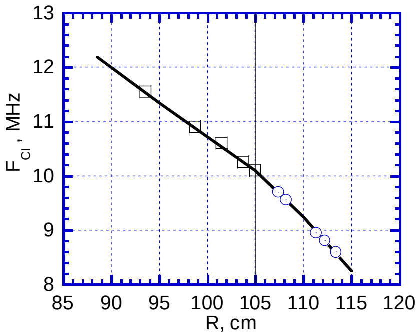

Fig.5. The ion cyclotron frequency along torsatron radius solid line was calculated from B(R), the points are result of back-scattered UHF signal analysis

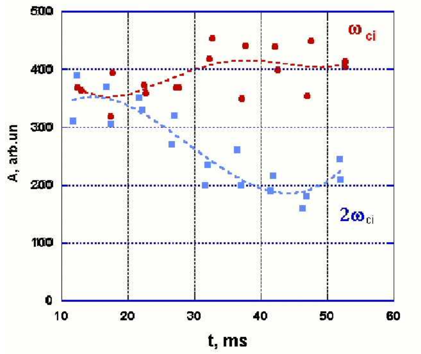

Fig. 6

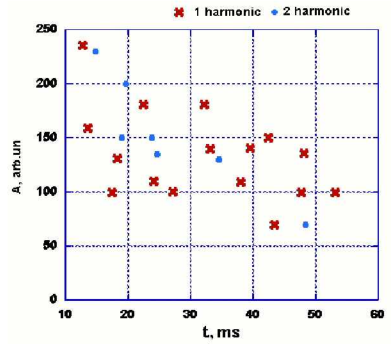

Fig.7

But these data were obtained for one regime of device operation and thus are preliminary.

Besides of spectrum of observed fluctuations we estimated the "radial" component of fluctuation wave vector k_f value. The simplest estimate of k_f comes from

$$\bar{k}_{ref} = k_{incid} + k_f \ ,$$

where k_{ref} and k_{incid} are k vectors of reflected and incident microwaves. For microwave backscattering the fluctuation wave vector modulus is

$$\left|k_f\right| = 2\left|k_{incid}\right| .$$

More accurate estimate of k_f given in [7] is

$$1.26 \cdot k_{incid}^{2/3} \cdot L^{-1/3} < k_f < 2 \cdot k_{incid} , \qquad (1)$$

where $L = \frac{n}{\nabla n}$, n – plasma density. At the experiment conditions ($n_{0\max}$ = $4 \cdot 10^{18}$ m^{-3}) a range of k_{incid} was 3.5…6 cm^{-1} and 2…4 cm^{-1} for outward and inward probing correspondingly. Thus the range of k_f coming from (1) is 3 cm^{-1} < k_f < 12 cm^{-1} and range of $k_f \rho_{L_i}$ is $0.5 < k_f \rho_{L_i} < 3$ (for T_i = 250 eV). It is necessary to notice that upper limit for observed k_f was determined by plasma density/cut-off probing frequency range in experiment.

It is worth to notice that we did not observe fluctuations with frequencies related to excited RF waves in spite of we observed the difference frequency of RF oscillators in the case when 2 RF antennas were powered [6]. RF waves were excited by antennas with much lower wave numbers ($k \approx 0.2$ cm^{-1}) and could not manifest at microwave backscattering.

3. CONCLUSIONS

All experimental data on studies of high frequency plasma density fluctuations for U-3M device confirmed theory predictions of possible excitation of short wavelength ion Bernstein waves with the frequencies $\omega \approx n\omega_{\text{ci}}$ and $k\rho_{L_i} \sim 3$. This conclusion is important for understanding of physics of ion heating at excitation of Alfven waves in U-3M plasma.

Theory predicts [4] that at the nonlinear stage the saturation of IBW occur due to the nonlinear broadening of cyclotron resonance because of the random walk of ions in the field of unstable IBW. The scattering of ions on turbulent fluctuations increases their "transverse" temperature. Experimental observation of IBW gives a tool for study of predicted link between IBW amplitude and ion temperature as well.

The ion cyclotron harmonics observation by microwave backscattering has diagnostic implications for U-3M. Measurement of ion cyclotron harmonic frequency F_{ci} for different values of probing frequency (cut-off frequency $F_{\text{cut-off}}$) allows to map F_{ci} over $F_{\text{cut-off}}$ and get a radial profile of electron density. We will use this approach in future experiments.

REFERENCES

1. V.V. Bakaev, V.V. Bronnikov, V.S. Voitsenya et al.// *VIII Intern. Conf. on Controlled Fusion Research.* London, 1984, v.2, p. 397.
2. N.T. Besedin, S.V. Kasilov, I.M. Pankratov, A.I. Pyatak and K.N. Stepanov // *X Intern. Workshop on stellarators.* Garhing, 1993, collection of papers, p. 277.
3. A.B. Kitsenko, V.I. Panchenko, K.N. Stepanov // *Zh. Techn. Fiz.*. 1973, v. 43, p. 1437 (in Russian).
4. V.S. Michailenko, K.N. Stepanov: Preprint KFTI 83-29, Kharkov, 1983; *Zh. Exp. Teor. Phyz.* 1984, v. 87, p. 161 (in Russian).
5. E.D. Volkov, V.L. Berezhnyj et al. // *Czechoslovak Journ. of Physics.* 2003, v. 53, p. 887.
6. O.S. Pavlichenko, A.I. Skibenko, E.D. Volkov, V.L. Berezhnyj et al. // *Problems of Atomic Science and Technology. Series "Plasma Physics"(11).* 2005, № 2, p. 17-19.
7. C.Fanack, I.Boucher, F.Clairet et al. // *Plasma Phys. Control Fusion.* 1996, v. 38, p. 1915.

ВОЗБУЖДЕНИЕ ПЛАЗМЕННЫХ ФЛУКТУАЦИЙ ВБЛИЗИ ИОННЫХ ЦИКЛОТРОННЫХ ЧАСТОТ ПРИ ВЧ-НАГРЕВЕ ПЛАЗМЫ В ТОРСАТРОНЕ УРАГАН-3М

А.И. Скибенко, О.С. Павличенко, В.Л. Бережный, П.Я. Бурченко, А.Е. Кулага, В.Л. Очеретенко, И.Б. Пинос, А.В. Прокопенко, А.С. Славный, И.К. Тарасов, О.Ю. Волкова

Бестоковая плазма в Урагане-3М создается и нагревается при поглощении ВЧ-мощности в области альфвеновских волн [1]. Процесс нагрева плазмы объясняется [2] черенковским поглощением энергии быстрых (ЭМ) и медленных (кинетических альфвеновских) волн электронами и турбулентным нагревом ионов из-за возбуждения коротких ионных Бернштейновских волн. В этой статье представлены результаты изучения флуктуаций плотности плазмы, которые наблюдаются в узкой полосе вблизи частот $\omega \approx n\omega_{\text{ci}}$ (n = 1, 2, 3).

ЗБУДЖЕННЯ ПЛАЗМОВИХ ФЛЮКТУАЦІЙ ПОБЛИЗУ ІОННИХ ЦИКЛОТРОНИХ ЧАСТОТ ПРИ ВЧ-НАГРІВІ ПЛАЗМИ В ТОРСАТРОНІ УРАГАН-3М

А.І. Скибенко, О.С. Павличенко, В.Л. Бережний, П.Я. Бурченко, А.Є. Кулага, В.Л. Очеретенко, І.Б. Пінос, О.В. Прокопенко, О.С. Славний, І.К. Тарасов, О.Ю. Волкова

Безструмова плазма в Урагані-3М створюється і нагрівається при поглинанні ВЧ-потужності в області альфвеновских хвиль [1]. Процес нагріву плазми пояснюється [2] черенковським поглинанням енергії швидких (ЕМ) та повільних (кінетичних альфвенівських) хвиль електронами і турбулентним нагрівом іонів при збудженні коротких іонних Бернштейновських хвиль. В даній статті представлені результати вивчення флуктуацій густини плазми, які спостерігаються в вузькій смузі поблизу частот $\omega \approx n\omega_{\text{ci}}$ (n = 1, 2, 3).