MEASUREMENT OF DISPERSION OF LOW-FREQUENCY ION OSCILLATIONS IN HYBRID PLASMA WAVEGUIDES

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A new technique of determining dispersion characteristics of the ion oscillations, excited in the hybrid plasma waveguide is elaborated (this device is a slow-wave structure, the passage channel of which is filled with plasma). This method is based on measuring changes in the shape of a single probing pulse propagating in the system. The method is tested in the process of determining the dispersion of low-frequency ion waves under the condition of the excitation of high-frequency powerful electron oscillations by an electron beam in the waveguide. The experimental data are compared with the analytical calculations.

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INTRODUCTION

The analysis given to the processes that takes place in beam-plasma (BP) microwave devices where hybrid plasma waveguides (HPW) [1,2] are used indicates that characteristics of these waveguides are prescribed not only by the microwave field structure in HPW but also by low-frequency (LF) ion oscillations. During the microwave excitation and maintenance of the beam-plasma discharge (BPD), a nonlinear coupling between electron microwaves and LF ion oscillations is established, which results in the augmentation of LF ion oscillation amplitude [3]. Excitation of LF oscillations brings substantial changes into the process of the BP instability development as well as into spectral and energy characteristics of the microwaves excited - even down to the derangement of the oscillation excitation itself [1-3]. It is impossible to understand the processes that cause the suppression of the microwave excitation in BP devices without studying the types of ion-plasma oscillations excited there (ω_{I}) and without information about their dispersion characteristics (DC).

The goal of our investigations is to study DC of LF oscillations excited in HPW-chain of cavities connected inductively (CCCI) under the condition of the plasma maintenance due to BPD in this chain.

DETERMINATION OF LF WAVE DISPERSION WITH THE HELP OF A SINGLE PROBING PULSE

Impossibility of installing probing- and receiving antennas in closed HPW hampers the measurement of DC of the waves excited in these waveguides by the methods available at present. The technique of determining DC of LF oscillations excited in HPW is elaborated. It is based on observing changes in the shape of a single probing pulse propagating in HPW.

Duration of the pulse excited in plasma $X_1(t)$ is chosen so that its frequency spectrum would belong to the resonance band of LF oscillations. While propagating in HPW, the pulse is subjected to the deformation conditioned by the HPW DC in this frequency range. Registering the pulse $X_2(t)$ that has passed the distance L along the plasma column, one can get the system DC in this frequency range:

$$Kz(\omega_{n})=1/L[\arg(F(X_1)_n) - \arg(F(X_2)_{n)}]$$

Here $Kz(\omega_{n})$ is the wave vector projection on the pulse propagation direction; $\omega=2\pi n/T$, $(1\leq n\leq N)$; T denotes the selection time; N=T/XT designates discretization period; L is the distance between the probes; $F(X_1)$ and $F(X_2)$ mark Fourier images of the input and output pulses [5-6].

To eliminate the signal phase discontinuity in vicinity to $2\pi n$, one must provide the realization of the condition of smallness of the phase difference between the neighboring frequencies in the discrete Fourier transform for both the signals: $X\varphi=\arg(F(X)_{n+1}/F(X)_n)<<\pi$. For justifying this criterion, the access time must be rather long. In practice, the access time duration is limited by the registering equipment capabilities. Thus, the time interval can be prolonged only by adding zeros to the measured signals [5-6], which introduces inevitable errors into the frequency characteristics obtained. However, by making use of single pulses for probing, one minimizes the errors conditioned by complementary zeros because such pulses are precisely localized in time.

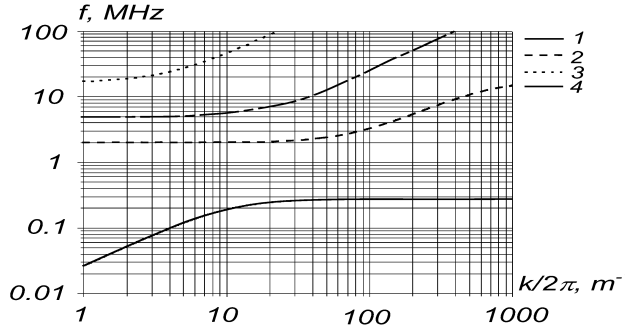


Fig.1

In Fig.1 one can see the dispersion curves for LF oscillations, obtained by numerical simulations of DC of LF oscillations for T- and H-waves. In this plot, the curve 1 describes the slow magnetic-acoustic wave. The curve 2 depicts the lowest radial harmonic of ion-acoustic (IA) oscillations. The curve 3 relates to the lowest radial harmonic of LH oscillations. These curves correspond to the plasma density $n=10^{11}$ cm^{-3}; the electron temperature T_e=100eV and the external magnetic field B=0.25 T. The curve 4 is plotted for LH oscillations when $n=6\cdot10^9$ cm^{-3}; T_e=(30-50)eV and B=0.25 T.

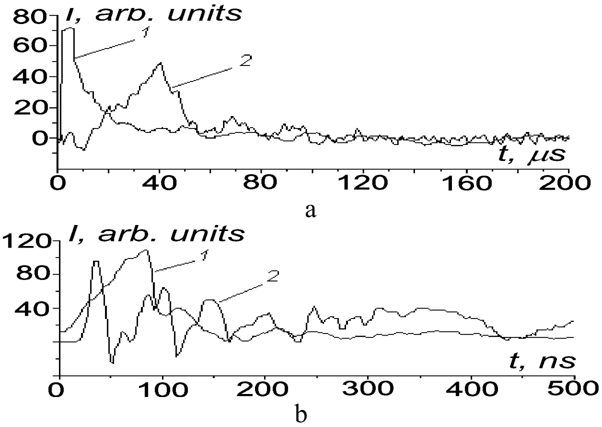
EXPERIMENTAL INVESTIGATIONS OF LF ION WAVE DISPERSION IN HPW BASED ON CCCI

The scheme of the test bench is described in [1,3]. Single pulses are sent both to a probe submerged into plasma and to the electron beam collector. The pulses transmitted through HPW system are registered with two single electron probes operating in the regime of saturation. The probes can be installed at the distance 512mm one from another, which overlaps the area of HPW location. Signals from the probes, after passing through the matching amplifier, are sent to the dual-channel analogous digital transducer (ADT) input. Further the probe signals are transmitted to PC for their processing. For measuring DC, we have used the single pulses of the duration 5 μs and 60 ns. The frequency spectrum of such pulses completely overlaps the range calculated for slow magnetic-acoustic (MA) - and low-hybrid (LH) waves, respectively.

In the tests, the plasma density in the waveguide ranges within (10^9 –$2\cdot10^{11}$) cm^{-3}. The electron temperature makes (25-100) eV. Microwaves are excited by the electron beam of the power from hundreds of W and up to 40kW. The plasma parameters are measured with double probes, installed at the edges of HPW.

Certain specificities have been found out during the study of the pulse propagation in the HPW plasma column.

The probing pulse of the duration 5 μs can be for sure registered only when microwave power is lower than 25kW. In this case, the duration of the pulse passing through HPW is prolonged.



a

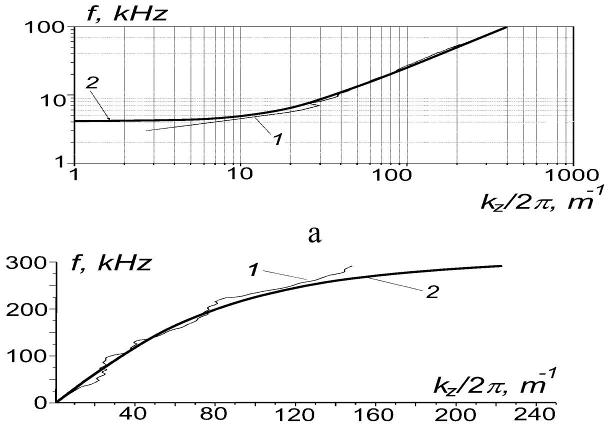
b

Fig.2

The pulse of the duration 60ns, the spectrum of which overlaps the LH wave frequency range, is detectable only when the microwave power is lower than 1kW and $n=10^{10}$cm^{-3}. The pulse is subjected to the substantial attenuation. It is significant that as the microwave power increases, the probing pulse “scatters” to a sequence of pulses of a shorter duration. In Fig.2, the oscillograms (a) and (b) illustrate the evolution of pulses of the duration 5 μs and 60 ns during their passage through HPW when microwaves are excited with the beams of the power 15kW and 0.7kW, respectively.

For LF oscillations, the dispersion characteristics (DC) are obtained by processing oscillograms of the single probing pulses passed through HPW according to the above-described technique (see Fig.3).

For comparison, in the same graph (Fig.3), we have placed DC for LH (a) and slow MA (b) waves. These dependences are calculated analytically for the two sets of the plasma parameters values, used in the tests: (a) corresponds to $n=6\cdot10^9$ cm^{-3} and T_e=(30-50)eV; (b) depicts the case of $n=10^{11}$ cm^{-3} and T_e=100eV. The external magnetic field B=0.25T in both the cases. As the given plots indicate, the curves simulated numerically with taking into account the pulse form evolution to a high precision coincide with the experimental results.



a

b

Fig.3

The dispersion characteristic of LH-waves indicates that their wavelength is short; its maximum does not exceeding 2cm. The wave phase velocity makes several units of 10^8cm·s^{-1}. This magnitude is more than by two orders smaller than the velocity of the beam generating plasma due to BPD.

For checking the results obtained within the shortest wavelength range, we have measured the wavelengths by the probing wave phase taper during the wave propagation in HPW plasma. The measurements are carried out at the frequencies (50, 60 and 71) MHz. In HPW, oscillations are excited with a helical aerial, fed from the oscillator at one of the frequencies mentioned. The probes are installed between the spiral and HPW (in vicinity to the passage channel) and also between HPW and the beam current collector.

In Fig.4, one can see oscillograms of the oscillations at the frequency 71 MHz. They are registered with probes installed at the distance 0.5 cm from the spiral (the waveguide input) and at the waveguide output (43 cm from the spiral). As the oscillograms indicate, at the distance 43 cm the oscillations are in antiphase. About 100 wavelengths can go into this distance.

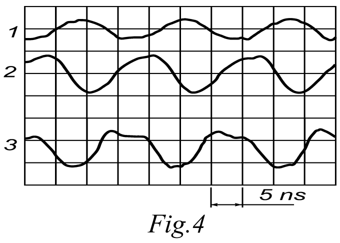


Fig.4

The results of this series of tests also confirm that LH wave branch does exist in HPW. However, as the data indicate, the evaluated difference between wavelength is twice as the deformation of the pulse propagating in HPW. At the same time, the propagation velocity is twice more**.** Discrepancies in the wave number values obtained by the two methods are conditioned by introducing a gross error into the measurement of the wave phase taper. These discrepancies are both conditioned by an intricate shape of the oscillations and smallness of the number of probes installed in the direction of the oscillation propagation. It is worth mentioning that the probing wave substantial attenuates as the power of microwaves excited by the beam increases.

CONCLUSIONS

Thus, as it is found out by analytical calculations and numerical simulations, the three branches of LF ion oscillations can be excited in HPW that has the form of CCCI channel with the plasma-filled passage: SMA-, IA- and LH ones. The existence of SMA- and LH waves is confirmed by the analysis given to the pattern of single pulse propagation in GPW.

The submitted method of measuring DC of HPW proper LF waves is based on detecting deformation of the single pulse propagating in this waveguide. This technique is rather effective if microwaves excited are characterized by relatively heavy power. Most probably, this method is inapplicable just either when there takes place a substantial attenuation of the microwaves that belong to the probing pulse inherent spectrum or in the cases of large amplitude of LF oscillations in plasma and that of the pulse that stimulates the wave nonlinear interaction development.

Very likely, the wave nonlinear interaction indicates itself via the emergence of a sequence of pulses, stimulated by a single pulse. Observed in the experiment, this phenomenon takes place when the microwave electric field strength in the waveguide exceeds a certain threshold value. As regards LH waves, in the experiment this parameter has reached 300V/cm. For IA waves, the electric field strength approaches the level 1800V/cm.

As it should be emphasized, the given technique of determining the proper wave DC implies that the pulse spectral composition does not get into the upper cutoff band in the dispersion curve. In this case, the pulse during its propagation is also transformed into a sequence of shorter pulses, and the wave DC restoration becomes impossible.

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REFERENCES

1. A.N. Antonov, Yu.P. Blioh, E.A. Kornilov et. al.// *Plasma Physics.* 2000, v. 26, №12, p.1097-1109.
2. Yu.P, Bliox, Ya.B. Fainberg, M.G. Lubarsky et. al. Report Conf on High-Power Particle Beams // *Beams 98.* HAIFA, ISRAEL 7-13, 1998, p. 286.
3. A.N. Antonov, E.A. Kornilov, O.F. Kovpik et. al.// *Plasma Physics.* 2001, v. 27, №6, p. 1-5.
4. V.S. Antipov, O.F. Kovpik, E.A. Kornilov, K.V. Matyash // *Materials of the 8th International Crimean conference.* 1998, v. 2, p. 711.
5. L.S. Bennet, Dg. Ross. The Time-Impulse Electromagnetic Processes and their Applications // *JEEE*, 1978, v. 66, №3, p. 35 (in Russian).
6. Dg.P. Endryus. Automatic Decision of Parameters of Electric Ehains by Means Measuring in the Temporary Realm // *JEEE.* 1978, v. 66, №4, p. 56-67.

ИЗМЕРЕНИЕ ДИСПЕРСИИ НИЗКОЧАСТОТНЫХ ИОННЫХ КОЛЕБАНИЙ В ГИБРИДНЫХ ПЛАЗМЕННЫХ ВОЛНОВОДАХ

В.С. Антипов, А.Н. Антонов, В.А. Балакирев, О.Ф. Ковпик, Е.А. Корнилов, К.В. Матяш, В.Г. Свиченский

Разработана методика определения дисперсионных характеристик волн, возбуждаемых в гибридном плазменном волноводе (замедляющая структура, пролётный канал которой заполнен плазмой), основанная на измерении изменения формы распространяющегося в системе одиночного зондирующего импульса. Испытание метода проведено при определении дисперсии низкочастотных ионных волн в условиях возбуждения в волноводе электронным пучком высокочастотных электронных колебаний большого уровня мощности. Проведено сравнение результатов эксперимента с теоретическими расчетами.

ВИМІРЮВАННЯ ДИСПЕРСІЇ НИЗЬКОЧАСТОТНИХ ІОННИХ КОЛИВАНЬ В ГІБРИДНИХ ПЛАЗМОВИХ ХВИЛЕВОДАХ

В.С. Антіпов, О.М. Антонов, В.А. Балакірєв, О.Ф. Ковпік, Є.О. Корнілов, К.В. Матяш, В.Г. Свіченський

Розроблена методика визначення дисперсійних характеристик хвиль, порушуваних в гібридному плазмовому хвилеводі (уповільнююча структура, пролітний канал якої заповнений плазмою), заснована на вимірюванні зміни форми одиночного зондуючого імпульсу, що розповсюджується в системі. Випробування методу проведено при визначенні дисперсії низькочастотних іонних хвиль в умовах збудження в хвилеводі електронним пучком високочастотних електронних коливань великого рівня потужності. Проведено порівняння результатів експерименту з теоретичними розрахунками.