BEAM INSTABILITY STABILIZATION IN HYBRID PLASMA WAVEGUIDE

A.N. Antonov, O.F. Kovpik, E.A. Kornilov, V.G. Svichensky

NSC Kharkov Institute of Physics & Technology, Kharkov, Ukraine

The authors submit the results of investigations of the beam-plasma instability derangement in the hybrid plasma waveguide. The latter, placed into the longitudinal magnetic field, consists of a chain of cavities connected inductively and its passage channel is filled with plasma. In this plasma, the excitation of low-frequency oscillations that belong to the low-hybrid resonance range is examined. The investigations are carried out in the beam-plasma oscillator. The plasma is generated and maintained due to the beam-plasma discharge.

PACS: 52.40.Mj

Earlier we have already investigated the excitation of microwaves by the electron beam at the plasma characteristic electron frequencies in the hybrid plasma waveguide (HPW). The investigations have indicated that the microwave power is to a considerable extent determined by low frequency (LF)- and ion oscillations of plasma [1,2]. A chain of inductively connected cavities with the plasma-filled passage channel is traditionally used for the beam-plasma (BP) oscillators and amplifiers [3]. Ion-acoustic (IA) and low-hybrid (LH) waves are LF proper waves of this waveguide [4].

Seemingly, the pressure of microwaves stimulated directly by the beam makes one of the most probable nonlinear mechanisms for the excitation of ion-acoustic oscillations in HPW [2]. As ion-acoustic oscillations come into existence, there arise temporal changes in the absolute magnitude of the plasma density and in its longitudinal gradient. These factors cause alterations both in the microwave excitation effectiveness and directly in the dispersion of the microwaves driven by the beam. As a result, both the microwave group velocity and the excited wave energy flow change directions of their motion. At the HPW edges, the amount of microwave maximum power is being periodically changed in time. [4]. Augmentation of the beam current is accompanied by an increase in the microwave power. However, when it achieves a certain threshold value, there occurs the microwave excitation derangement [1-2]. Even if the excitation still takes place, there arise just separate sporadic pulses, short in a space of time. Before the derangement, one can always detect an increase in amplitudes of LF oscillations of the low-hybrid range. It is perfectly legitimate to suppose that these LF oscillations make a certain contribution to the microwave excitation derangement. As it is known, if BP discharge is unbounded in its radius, the excitation of LF oscillations from the low-hybrid resonance area is accompanied by the acceleration of plasma ions and their heating as well as by the plasma going away from the beam area along the beam radius. That is, the process of excitation of LF oscillations is accompanied by a decrease in the plasma density in the beam area [5]. Via the mechanism for the nonlinear coupling with microwaves, LF oscillations make a certain contribution to stochastization of microwaves so that they become irregular. In this case, the electron beam of a narrow energy spectrum, continuously coming to HPW, is incapable of any effective transfer of its energy to irregular waves. This can result in the microwave excitation derangement [6]. In HPW, where BP discharge maintains plasma, can take place these processes as well. This supposition is confirmed by a series of the tests performed by the authors (for this purpose, we used the installation, where the dispersion of HPW proper LF waves had been measured earlier [7]). The method of introducing external disturbances into HPW is applied. These disturbances have the form of a probe wave, the frequency of which belongs to the low-hybrid oscillation range. Short LH waves are excited with a helical aerial, fed from a driving oscillator with the tunable frequency. The spiral, installed in front of HPW, is axially-symmetric with respect to the electron beam, injected into HPW. The waveguide is located in the homogeneous magnetic field (up to 0.2 Tl). In the tests, the beam energy ranges within (10-20) keV and the current is (1-10)A per pulse of the duration 2 ms. The power of the oscillations under excitation at the frequencies (4-4.5)GHz varies from 100W up to 40kW. The nitrogen pressure in the chain of inductively connected cavities varies within $(1.33 \cdot 10^{-2}$-$1.33 \cdot 10^{-1})$ Pa. The oscillation power transferred from the driving oscillator to the spiral does not exceed 100 W at the frequencies (50-75) MHz per pulse of the duration 250 μs.

Let us dwell on certain specificities of correlation between microwaves excited by the beam and LF waves from the low-hybrid range, detected when BP discharge is being maintained in HPW.

I. If regular microwaves are excited by the electron beam at the frequency ω_0, the introduction of a wave at the frequency ω_h from LH-range into the HPW plasma is accompanied by the emergence of the combination frequency $\omega = \omega_0 - \omega_h$ in the spectrum ω_0. The amplitude of microwaves at the frequency ω_0 decreases. To restore the amplitude initial value, it is necessary to augment the energy of the beam injected into HPW.

The combination oscillation amplitude increases as the microwave amplitude grows. At the same time, the probing LH wave, excited by the oscillator and propagating in HPW, is being attenuated if the beam parameters are fixed. This specificity of the generated wave behavior indicates that the energy is continuously being transmitted from microwaves excited by the beam to LH waves.

As the amplitude of excited probing LF waves increases, the phase velocity of LH waves increases as well. To start from a certain amplitude value, there arise harmonics and the probing wave is subjected to bifurcation. That is, in the dispersion function of LH waves D(ω ,k), which determines their phase velocity in plasma of HPW, the wave vector k depends on the wave field strength. LH waves are nonlinear if the microwave power takes the above-mentioned value. Generation of high-frequency components and their harmonics in the LF oscillation spectrum is detected experimentally already when the microwave field strength is on the order of hundreds of V/cm (see [7]).

In Fig.1, one can see the oscillograms that depict changes in the frequency and amplitude of the LH wave, excited by the oscillator, after the wave passage through HPW. It is clearly demonstrated that at the HPW output the frequency has reached the value 4 times as high, whereas the amplitude has become 5 times as small.

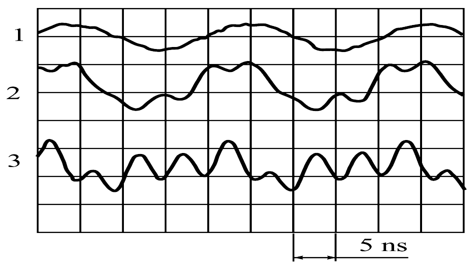

Fig.1. Evolution of the probing signal during its propagation through HPW

The following designations are used:
1 - marks the oscillations excited in plasma by the master oscillator at the frequency 47.9MHz;
2 - denotes the oscillations registered with the probe at the beam input into HPW;
3 - designates oscillations registered with the probe at the HPW output (the oscillograph sensitivity is 5 time as high as in the oscillograms 1 and 2).

II. A certain regular dependence is established between amplitudes of LH oscillations and microwaves. The higher is the LH waves amplitude assigned, the smaller is the critical power of microwaves excited by the beam in HPW. That is, one can observe a diminution in the microwave power amount, the excess over this limit is accompanied by the microwave derangement. This fact indicates that not only ion-acoustic waves [2] but also LH ones affect the limiting values, imposed on the microwave power amount attainable in BP-oscillator that contains HPW.

In Fig.2, oscillograms illustrate the microwave suppression during the LH wave excitation in HPW. In the upper oscillogram, the detected pulse of LF oscillations, sent to the spiral from the master oscillator, is presented. In the lower oscillogram, one can see the signal, coming from microwaves excited by the beam of the power 30 kW and detected at the HPW output section.

The oscillograms demonstrate that the oscillation excitation by the master oscillator is accompanied by the total suppression of microwaves. Tracing the process of changes in the power of microwaves excited by the beam during the duration of LF oscillation power pulse, transferred to the spiral aerial, one can notice the following pattern.

If the LF oscillation power is introduced (at the pulse leading edge), the amount of which makes (15-20)% of the value that corresponds to the microwave suppression, the microwave power decreases in time by (50-80)% approximately in the direct proportion. However, up to 80% of the LF oscillation power is required for the microwave total suppression (20%). Besides, before the total derangement, there always exists a stage, during which the microwave amplitude steeply decreases (the stage duration is rather short - several μs). In the experiment, when the LF oscillation power pulse leading edge makes 60 μs, the first stage lasts approximately during (10-15)μs, the final stage duration is (2-5)μs.

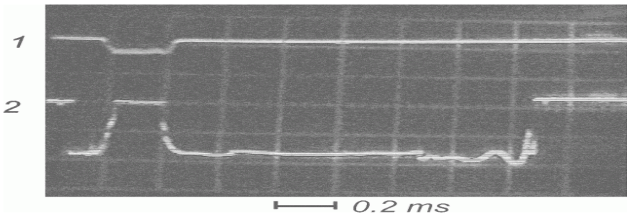

Fig.2. Oscillograms of envelopes of the oscillations from the LH range, excited by the oscillator at the frequency 70MHz, and the envelope of oscillations in the band 4GHz, excited by the electron beam (the pulse power is 30kW)

At the same time, the process of restoration of microwave excitation is of “explosive” nature. Microwave power is restored up to 70% at the LF oscillation probing pulse rear edge during the time shorter than 5μs. The functional dependence of microwave power (*P*) restoration in time has the following form:

$$P \approx A_0^2 \cdot \left(1 - e^{(t_0 - t)/3.2109}\right)$$

Here A_0 is the amplitude of microwaves excited by the beam in the absence of the probing LF signal; t_0 denotes the time corresponding to the end of the probing pulse plateau; t is running time.

The character of temporal changes in the microwave amplitude, observed under the condition of alterations in the amount of the probing signal power transferred to the antenna, additionally confirms the existence of LF wave absorption. That is, the nonlinear coupling between microwaves and LH LF waves is realized under the condition of strong absorption of the latter in plasma. One of the consequences of this absorption can become the gas extra ionization so that the plasma density increases. The following fact can indirectly confirm this statement. For the maintenance of the effective excitation of microwaves by the beam when the probing LF signal is sent, the beam energy must be augmented. As it is known [7], the electron wave phase velocity increases as the plasma density in the waveguide grows.

The authors consider that the oscillograms in Fig.2 confirm that LH wave amplitudes affect the process of microwave excitation in BP oscillator. One can suppose that only the mechanisms for suppressing LF oscillations from LH wave range can permit augmenting the maximum amount of microwave power, attainable in HPW of BP oscillator.

CONCLUSIONS

Generally speaking, the results of the given work and the works fulfilled earlier [1-4] confirm that the HPW proper LF ion oscillations play an important role in the excitation of microwaves by the electron beam. LF oscillations are excited due to the plasma non-linearity in the BP discharge.

Excitation of ion-acoustic oscillations in HPW is accompanied by the formation of the plasma density longitudinal gradient during certain time intervals. This gradient maintains the auto-resonance between the beam losing the energy in HPW and the microwave excited. During these time intervals, the microwave electric field strength in plasma increases up to the value, under which the microwave “splits” to one of the HPW proper microwave modes and a LH wave. In the long run, an increase in the amplitude of the latter causes the beam instability derangement, “extinction” of BP discharge and sporadic generation of microwave short single pulses.

The totality of the results of the investigations indicates the following. Microwaves in BP system of HPW can be stable and regular only when their power does not reach a critical value, under which the excitation of long-wave LF ion oscillations in plasma becomes possible due to the microwave pressure.

In BP oscillator, a large amount of power and a high efficiency are obtainable when the device operates in vicinity to the critical power value. Besides, the HPW input and output sections must be connected to a common load. In BP microwave devices where HPW is used, high power is obtainable if the waveguide cross-section of a large size is taken. As it is known, the power at the oscillator output is field strength, the wave group velocity and the plasma cross-

section in the waveguide. Consequently, if the wave electric field strength is fixed, the oscillator power is directly proportional to the HPW cross-section size and to the coefficient of coupling with the electron beam. Seemingly, for BP-oscillator or a high-power microwave amplifier, a waveguide in the form of a coaxial line, loaded with disks on both electrodes and the passage channel filled with plasma is one of prospective models of HPW [8,9].

The authors are grateful to A.P. Tolstolugsky for the calculation of the spiral aerial, loaded with plasma and to L.D. Lobzov for the oscillator adjustment. S.S. Pushkarev’s help in the elaboration of the technique of registering the probing pulses in plasma with probes is gratefully acknowledged. We also wish to thank V.A. Buts for the discussion of the results and valuable suggestions in the course of the work fulfillment.

REFERENCES

1. V.S. Antipov, A.N. Antonov, V.A. Balakirev et al. // *Report Conf. on High-Power Particle Beams. BEAMS’98, Haifa, Israel 7-12, 1998*.

2. Yu. P, Bliox, Ya. B. Fainberg, M.G. Lubarsky et al. // *Report Conf on High-Power Particle Beams. BEAMS’98, Haifa, Israel 7-12, 1998.* p. 286.

3. Ya.B. Faynberg, Yu.P. Blioh, E.A. Kornilov et al. // *Reports of Ukraine AS*, 1990, №11, p. 55 (in Ukrainian).

4. A.N. Antonov, Yu.P. Blioh, E.A. Kornilov et al. // *Plasma Physics*. 2000, v.26 №12. p. 1097-1109.

5. V.A. Buts, O.F. Kovpik, E.A. Kornilov. Wave Nonlinear Interaction Effect on Beam-Plasma Reciprocal Influence // *Problems of Atomic Science and Technology.* This number, p.131-133.

6. V.A. Buts, I.K. Kovalchuk, E.A. Kornilov, D.V Tarasov // *Problems of Atomic Science and Technology*. 2003 №4, p.109.

7. V.S. Antipov, A.N. Antonov, V.A. Balakirev, O.F.Kovpik, E.A. Kornilov, K.V. Matyash, V.G.Svichensky. Measurement of Dispersion of Low-Frequency Ion Oscillations in Hybrid Plasma Waveguides // *Problems of Atomic Science and Technology*. This number, p.149-151.

8. E.A. Kornilov, O.M. Korostilev, A.V. Lodigin et al. // *Ukrain Ph. J.* 1995, v. 40 №4, p. 312-317 (in Ukrainian).

9. B.I. Markov, V.S. Antipov, I.N. Onishchenko, G.V.Sotnikov // *Problems of Atomic Science and Technology. Ser.: “Plasma Physics”*. 2002, №5, p. 86.

СТАБИЛИЗАЦИЯ ПУЧКОВОЙ НЕУСТОЙЧИВОСТИ В ГИБРИДНОМ ПЛАЗМЕННОМ ВОЛНОВОДЕ

А.Н. Антонов, О.Ф. Ковпик, Е.А. Корнилов, В.Г. Свиченский

Приведены результаты исследования срыва пучково-плазменной неустойчивости в гибридном плазменном волноводе, помещенном в продольное магнитное поле, состоящем из цепочки индуктивно связанных резонаторов, пролетный канал которой заполнен плазмой, при возбуждении низкочастотных колебаний в его плазме из области нижнегибридного резонанса внешним генератором. Гибридный плазменный волновод используется в пучково-плазменном генераторе. Плазма образовывается и поддерживается за счет пучково-плазменного разряда.

СТАБІЛІЗАЦІЯ ПУЧКОВОЇ НЕСТІЙКОСТІ В ГІБРИДНОМУ ПЛАЗМОВОМУ ХВИЛЕВОДІ

О.М. Антонов, О.Ф. Ковпік, Є.О. Корнілов, В.Г. Свіченський

Приведені результати дослідження зриву пучково-плазмової нестійкості у гібридному плазмовому хвилеводі, розміщеному в поздовжньому магнітному полі, що складається з ланцюга індуктивно зв'язаних резонаторів, пролітний канал якого заповнений плазмою, при збудженні низькочастотних коливань в його плазмі із області нижнєгібридного резонансу зовнішнім генератором. Гібридний плазмовий хвилевід використовується в пучково-плазмовому генераторі. Плазма створюється і підтримується за рахунок пучково-плазмового розряду.