SURFACE WAVE CONTROL IN PLASMA-METAL STRUCTURES WITH PERPENDICULAR MAGNETIC FIELD

Yu.A. Akimov, N.A. Azarenkov, V.P. Olefir
Department of Physics and Technology, Institute of High Technologies, Kharkiv National University, Kharkiv, Ukraine,
E-mail: olefir@pht.univer.kharkov.ua; Fax: (057) 3353977; Tel: (057) 3350509

The nonlinear interaction of high-frequency potential surface waves at a dense magnetized plasma-metal interface with a low-frequency plasma density modulation is considered in the point of view to control the surface waves. The influence of an external steady magnetic field directed perpendicularly to the interface and plasma parameters on temporal dynamics of the waves is studied.
PACS: 52.35.Mw

1. INTRODUCTION

At the present time plasma-metal waveguides are widely used in plasma and semiconductor electronics, gas discharges, and various plasma technologies [1]. It causes the intensive theoretical and experimental studies of wave processes in plasma-metal structures.

In practice many types of waveguide structures operate with a magnetic field oriented perpendicularly to a plasma-metal boundary [2-5]. Such waveguides are typical of RF and microwave discharge, magnetrons, Penning sources, magnetic discharge pumps, Hall detectors, divertor- and limiter-equipped fusion systems, and so on. Especially such configuration of magnetic field is very important for plasma processing, because the best macroscopic processing uniformity is achieved when the magnetic field is perpendicular to the substrate.

As well known, the propagation of SWs at a cold plasma-metal interface with a perpendicular magnetic field is impossible, whereas it is possible in a warm plasma. The linear theory of potential SWs at a plane boundary of a warm plasma with a metal in such magnetic field configuration has been considered in [2, 3]. Some nonlinear mechanisms of these SWs at a dense plasma have been investigated, for example, in [6, 7].

In order to control the SWs, their nonlinear attenuation due to the nonlinear dynamics of the plasma particles can be used. In this paper we pay attention to the control of the high-frequency SW at the presence of a normal to the plasma-metal interface steady magnetic field by means of a low-frequency plasma density modulation.

2. FORMULATION

Let us consider a planar waveguide structure consisting of a nonisothermal ($T_e >> T_i$, where T_e and T_i are the electron and ion plasma temperatures, respectively) magnetized plasma that occupies the half-space $x > 0$ and is bounded in the plane $x = 0$ by a perfect conducting metal. An external steady magnetic field is supposed to be directed along the axis x.

According to paper [2], a finiteness of the electron thermal velocity V_{Te} in such planar waveguide structures causes the existence of high-frequency (HF) potential SWs in the frequency region greater than the electron cyclotron frequency. Below we will consider the HF SW in a high-density plasma, when the SW frequency is into the range $\omega_{ce}^2 < \omega_1^2 << \omega_{pe}^2$, where ω_{ce}, ω_{pe} are the electron cyclotron and plasma frequencies, accordingly. Hereinafter all quantities corresponding to the HF SW of a finite amplitude we will note with the index 1, so in this frequency region the HF SW potential can be written in the following form:

$$\varphi_1 = A_1[\exp(-\lambda_1' x) - \exp(-\lambda_1'' x)]\exp[i(k_1 y - \omega_1 t)] \quad , (1)$$

where A_1 is the HF SW amplitude, λ_1' and λ_1'' determine penetration depth of the wave fields into the plasma. The wavenumber k_1 is given by:

$$k_1 = \omega_1 / V_{Te} \sqrt{(\omega_1^2 - \omega_{ce}^2)/\omega_{pe}^2} \, . \qquad (2)$$

In order to study a possibility of the SW control, let us consider the nonlinear interaction of HF SW with a low-frequency (LF) plasma density modulation $\delta n(\vec{r}, t) = \delta n(x)\exp[i(k_2 y - \omega_2 t)]$. The LF wave frequency ω_2 and its wavenumber k_2 are supposed to be such that $|\omega_2| << |\omega_1|$, $|k_2| << |k_1|$. It is well known that a plasma density modulation can essentially influence on SW stability. Below we will consider the following three low-frequency regions:

$$1)\ \omega_2^2 << \omega_{ci}^2,\ \omega_{pi}^2; \qquad 2)\ \omega_{ci}^2 << \omega_2^2 << \omega_{pi}^2; \qquad 3)\ \omega_{ci}^2,\ \omega_{pi}^2 << \omega_2^2 << \omega_{ce}^2$$

(ω_{ci}, ω_{pi} are the ion cyclotron and plasma frequencies). An interaction of those modulations with the HF wave results in the excitation of long-wave ($k_- = k_1 - k_2$, $\omega_- = \omega_1 - \omega_2$) and short-wave ($k_+ = k_1 + k_2$, $\omega_+ = \omega_1 + \omega_2$) satellites of the HF SW. In such system two kinds of interaction of HF, LF waves and satellites are possible [8]. The resonant interaction is realized, when one of the satellites and the LF perturbation are eigen waves of the waveguide structure. Another kind of interaction is non-resonant, when only the satellites are eigen.

One can show that in such structure the conditions of resonant interaction are not fulfilled, whereas the non-resonant type of interaction is possible. It takes place, when the LF wave has a phase velocity which is close to the HF SW wave group velocity $V_{gr} = \partial\omega_1/\partial k_1$:

$$\omega_2 = \sum_{n=0}^{\infty} [k_2^{2n+1}/(2n+1)!]\partial^{2n} V_{gr}(k_1)/\partial k_1^{2n} \approx k_2 \quad (3)$$

One can show, the LF wave with dispersion relation (3) can be represented as a superposition of the forced oscillations of surface and volume types. Thus, in the structure under consideration the nonlinear dissipation of the HF wave energy takes place. It is caused by HF wave energy transport from the interaction region near the plasma-metal interface deep into plasma by the radiation part of the LF wave.

3. HF SW INSTABILITY CRITERION

The volume part of the LF plasma density perturbations results in an additional attenuation of the HF surface wave. In order to study this phenomenon, let us, following to [8], write the nonlinear equation set for the HF SW and its satellites, which corresponds to the nonlinear dispersion relation:

$$i\left(\frac{\partial A_1}{\partial t} + V_{gr}\frac{\partial A_1}{\partial y}\right) + i\nu_1 A_1 = Q^{*}(A_1 A_+^{*} + A_1^{*} A_-)A_- \quad Q(A_1^{*} A_+ + A_1 A_-^{*})A_-,$$

$$i\left(\frac{\partial A_+}{\partial t} + V_{gr}\frac{\partial A_+}{\partial y}\right) + i\nu_1 A_+ = Q(A_1^{*} A_+ + A_1 A_-^{*})A$$

$$i\left(\frac{\partial A_-}{\partial t} + V_{gr}\frac{\partial A_-}{\partial y}\right) + i\nu_1 A_- = Q^{*}(A_1 A_+^{*} + A_1^{*} A_-)A \quad (4)$$

where ν_1 is a linear decrement of the collision attenuation of the HF surface wave and its satellites; parameter Q is complex and defined by considered LF regions:

$$1)\ Q = -\frac{i}{16}\frac{e^2}{m_e^2 V_{Te}^4}\frac{\omega_2^2|\omega_{ci}|}{\omega_{pi}^3}\frac{(\omega_1^2-\omega_{ce}^2)^{3/2}}{\omega_1\omega_{pe}};$$

$$2)\ Q = -\frac{i}{16}\frac{e^2}{m_e^2 V_{Te}^4}\frac{\omega_{pe}^5\,\omega_2^4(\omega_1^2-\omega_{ce}^2)^{3/2}}{\omega_{pi}^6\,\omega_1(2\omega_1^2-\omega_{ce}^2)^2}; \quad (5)$$

$$3)\ Q = -i\frac{5}{3}\frac{e^2}{m_e^2 V_{Te}^4}\frac{\omega_1^3|\omega_{ce}|(\omega_1^2-\omega_{ce}^2)^{3/2}}{\omega_2^2(2\omega_1^2-\omega_{ce}^2)^2}.$$

Due to the complication of this equation set, it can be investigated only numerically. Below we will consider the temporal variation of the HF SW and its satellites amplitudes in the case, when $\partial A_{1\pm}/\partial y = 0$. The results of numerical solution of the LF perturbation amplitude are represented in fig. 1.

In a case of rather small initial values of the HF SW amplitude, when $|Q||A_{10}|^2/\nu_1 << 1$ (hereinafter the index 0 corresponds to the initial values of the wave amplitudes), the LF wave attenuation can be described by $|A_2| = |A_{20}|\exp(-2\nu_1 t)$. It means, the HF SW and its satellites attenuation is caused only by electron collisions. But, if the following condition

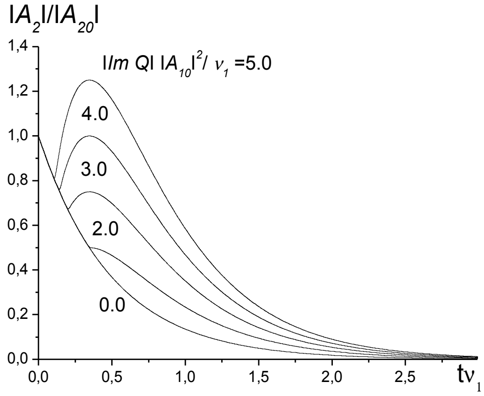

Fig. 1. Time evolution of the LF perturbation amplitude for different values of the parameter $|Q||A_{10}|^2/\nu_1$

$$|Q||A_{10}|^2/\nu_1 > 4 \quad (6)$$

is fulfilled then at initial stage of the waves interaction a growth of the LF perturbations and satellites with a simultaneous decrease of the HF SW amplitude takes place.

Thus, an increase of the parameter $|Q||A_{10}|^2/\nu_1$ leads to a more intensive growth of the LF wave amplitude and to a more intensive attenuation of the HF SW, consequently. The condition (6) corresponds to the case, when a growth of the satellites due to their nonlinear interaction with the HF and LF waves exceeds their collision decrease. This condition determines an amplitude threshold value of the HF SW, at which the instability is possible.

The carried out analysis has shown that the SWs of a small amplitude are stable with respect to the low-frequency plasma density modulation for the frequency region $\omega_2^2 << \omega_{pi}^2, \omega_{ci}^2$ and unstable for $\omega_{ci}^2 << \omega_2^2 << \omega_{pi}^2$ and $\omega_{ci}^2,\ \omega_{pi}^2 << \omega_2^2 << \omega_{ce}^2$.

In the second range, $\omega_{ci}^2 << \omega_2^2 << \omega_{pi}^2$, the HF SW amplitude threshold $|A_{10}|_{cr}$, at excess of which the SW instability appears, grows with an increase of the electron temperature and the plasma density and decreases with frequency ω_2 : $|A_{10}|_{cr} \propto \omega_2^{-2} n_o^{1/4} V_{Te}^2$. An increase of the external magnetic field results in growth of value $|A_{10}|_{cr}$. Thus, the most influence of the plasma density modulation is achieved at rather high frequencies $\omega_2 \approx 0,3\,\omega_{pi}$ in the limit of unmagnetized plasma with rather small density and weak electrons thermal motion.

In the third LF range, $\omega_{ci}^2, \ \omega_{pi}^2 << \omega_2^2 << \omega_{ce}^2$, the SW initial amplitude threshold $|A_{10}|_{cr}$ grows with the electron temperature and the LF plasma density modulation frequency as $|A_{10}|_{cr} \propto \omega_2 V_{Te}^2$. The analysis of magnetic field influence on $|A_{10}|_{cr}$ shows, the threshold value has a minimum at $\omega_{ce} = \sqrt{2/5}\,\omega_1$. Thus, the most influence of the plasma density modulation takes place in the region of rather high frequencies when $\omega_2 \approx 3\ \omega_{pi}$, as well as in the case of a weak electron thermal motion of the plasma immersed in a steady magnetic field with intensity close to $\sqrt{2/5}\,\omega_1 m_e c/e$.

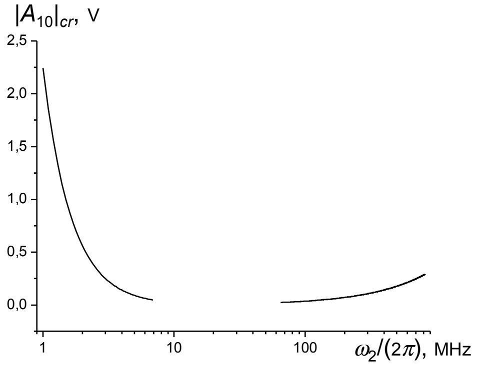

Fig.2. Influence of ω_2 *on* $|A_{10}|_{cr}$

Below we will estimate the initial HF SW amplitude threshold in the case of etching of tungsten films in a magnetoplasma sustained by microwaves. Under the experimental conditions [9] the low-pressure pure SF_6 discharge for electron cyclotron resonance etching is characterized by the pressure p =5 mTorr, plasma density $n_o \approx 1.3 \cdot 10^{12}$ cм$^{-3}$, average electron temperature 3.2 eV and electron collision frequency ν_1 =50 MHz, immersed into the magnetic field $H_o \approx 875$ Oe. In that case the instability of HF SW with $\omega_1/(2\pi) = \omega_{pe}/(4\pi) =$ 5 GHz relatively to the LF perturbations from the range $\omega_2/(2\pi)$ =(1 ¿ 7) MHz appears at small enough amplitudes: $|A_{10}|$ > (2.25 ¿ 0.045) V (see fig.2). It corresponds to $|E_{10}|$ >(1.11 ¿ 0.023) kV/cm for the HF SW electric field at the plasma-metal interface. Relatively to the LF modulation from the range $\omega_2/(2\pi)$ =(65 ¿ 825) MHz, the FH SW is unstable at $|A_{10}|$ >(0.021 ¿ 0.3) V or $|E_{10}|$ >(0.11 ¿ 0.144) kV/cm.

These estimates show that, under the etching conditions [9], the low-frequency plasma density modulation from the ranges $\omega_{ci}^2 << \omega_2^2 << \omega_{pi}^2$ and $\omega_{ci}^2, \ \omega_{pi}^2 << \omega_2^2 << \omega_{ce}^2$ can be effectively used for the HF SWs control, in contrast to the case of $\omega_2^2 << \omega_{ci}^2, \ \omega_{pi}^2$.

REFERENCES

[1] M. Moisan, J. Hurbert, J. Margot, Z. Zakrzewski. The Development and Use of Surface-Wave Sustained Discharges for Applications // *Advanced Technologies Based on Wave and Beam Generated Plasmas* / Academic Publisher, Kluwer, Amsterdam, 1999, pp. 1-49.

[2] N.A. Azarenkov, A.N. Kondratenko, Yu.O. Tishetskiy // *Tech. Phys.* (69). 1999, p. 30.

[3] Yu.A. Akimov, N.A. Azarenkov, V.P. Olefir // *Phys. Scr.* (70). 2004, p. 33.

[4] D.P. Schmidt, N.B. Meezan, W.A. Hargus Jr, M.A. Cappelli // *Plasma Sources Sci. Technol.* (9). 2000, p. 68.

[5] A.V. Nedospasov, M.Z. Tokar' // *Sov. Voprosy teorii plasmy.* (18). 1990, p. 68.

[6] N.A. Azarenkov, Yu.A. Akimov, V.P. Olefir // *Tech. Phys.* (49). 2004, p. 39.

[7] N.A. Azarenkov, Yu.A. Akimov, V.P. Olefir // *Plasma Phys. Reports.* (29). 2003, p. 669.

[8] J.C. Weiland, H. Wilhelmsson. *Coherent non-linear interaction of waves in plasma*. Oxford: "Pergamon press", 1977.

[9] F. Bounasri et al. // *J. Appl. Phys.* (77). 1995, p. 4030.

УПРАВЛЕНИЕ ПОВЕРХНОСТНЫМИ ВОЛНАМИ В ПЛАЗМЕННО-МЕТАЛЛИЧЕСКИХ СТРУКТУРАХ С ПЕРПЕНДИКУЛЯРНЫМ МАГНИТНЫМ ПОЛЕМ

Ю.А. Акимов, Н.А. Азаренков, В.П. Олефир

Рассмотрена возможность использования нелинейного взаимодействия высокочастотных поверхностных волн, распространяющихся на границе "плотная магнитоактивная плазма-металл", с низкочастотными возмущениями плотности плазмы для управления поверхностными волнами. Исследовано влияние постоянного магнитного поля, перпендикулярного границе, и параметров плазмы на временную динамику волн.

КЕРУВАННЯ ПОВЕРХНЕВИМИ ХВИЛЯМИ У ПЛАЗМОВО-МЕТАЛЕВИХ СТРУКТУРАХ ІЗ ПЕРПЕНДИКУЛЯРНИМ МАГНІТНИМ ПОЛЕМ

Ю.О. Акімов, М.О. Азаренков, В.П. Олефір

Розглянуто нелінійну взаємодію високочастотних поверхневих хвиль, що розповсюджуються вздовж межі густої магнітоактивної плазми з металом, із низькочастотними збуреннями густини плазми з точки зору контролю за поверхневими хвилями. Вивчено вплив зовнішнього магнітного поля, перпендикулярного до межі розподілу, та параметрів плазми на часову динаміку хвиль.