EXCITATION OF LANGMUIR OSCILLATIONS IN A SEMI-INFINITE DENSE PLASMA BY LASER PULSE

V.A. Balakirev, I.V. Karas', V.I. Karas', Ya.B. Fainberg, A.P. Tolstoluzhsky

NSC "Kharkov Institute of Physics & Technology", NAS of the Ukraine, Kharkov, Ukraine, e-mail: karas@ kipt.kharkov.ua

Nonlinear mechanism of Langmuir wave excitation in dense plasma by intensive laser pulse has been investigated. Laser pulse has frequency $\omega=\omega_p/2$ (where ω_p is electron plasma frequency).

PACS: 52.25.Dg, 52.65.Ff, 29.17.+w

1. INTRODUCTION

The study of physical mechanisms of a Langmuir wave excitation in plasma by a laser radiation is of interest for series of applications and first of all for processes of acceleration in plasma of electrons and ions (a modern state of this problem can see from articles [1-7], and references therein). In the present article a nonlinear mechanism of a Langmuir wave excitation by laser pulse which frequency is equal to half of plasma frequency is explored. Such pulse on the one hand have skin-depth of penetration in plasma, and with another – currents induced in plasma and charges on a second harmonic of radiation are in a resonance with Langmuir oscillations.

2. A STATEMENT OF PROBLEM. THE BASIC EQUATIONS

From vacuum on semi-infinite homogeneous plasma normally to its boundary a laser pulse with the given profile of intensity is incident. A frequency of laser pulse ω is twice lower than an electron plasma frequency ω_p. Such pulse have skin-depth of penetration in plasma**.** For the indicated frequency a nonlinear current in plasma (ponderomotive force) will have a plasma frequency and, hence, in skin-layer there will be a resonance excitation of Langmuir waves which from area of a radiant will be propagate deep into plasmas.

The initial set of equations contains: equations of motion of an electron component of plasma

$$m\left(\frac{\partial \vec{V}}{\partial t}+(\vec{V}\,\nabla)\vec{V}\right)=-e\vec{E}-\frac{e}{c}[\vec{V}\times\vec{H}]-\frac{V_{Te}^2}{n}\nabla n \quad (1)$$

an equation of a continuity and also Maxwell equations for an electromagnetic field (V_{Te} is a thermal electron velocity, $\vec{V}$ is electron velocity, n is an electron density). After realization of an average procedure we obtain an expression for nonlinear force.

$$\vec{F}_{nl}=\frac{e^2}{4m\omega^2}(\nabla\vec{E}_t^2 e^{-2i\omega t}+\kappa.c.). \quad (2)$$

The set of equations for longitudinal perturbations is equivalent to an equation for a longitudinal electric field of a Langmuir wave. In a situation considered by us in plasma the laser radiation intensity damps under the law

$$a^2=a_0{}^2F(t/t_L)\exp(-2\kappa z), \quad a^2=\frac{e^2\vec{E}_t{}^2}{m^2c^2\omega^2},$$

$$\kappa=\frac{\omega}{c}\sqrt{-\varepsilon(\omega)}=\frac{\sqrt{3}}{2}\frac{\omega_p}{c}, \quad \varepsilon=1-\frac{\omega_p{}^2}{\omega^2} \quad (3)$$

ε is an permittivity of plasmas. Function $F(t/t_L)$ describes a laser pulse profile, t_L - the reference duration of laser pulse. With the account (3) equation for a Langmuir wave field can be noted as follows

$$\frac{\partial^2 E_l}{\partial t^2}+\omega_p{}^2E_l-v_{Te}{}^2\frac{\partial^2 E_l}{\partial z^2}= =-\omega_p{}^2\frac{mc^2}{e}\kappa a_0{}^2F(t/t_L)\cos\omega_p t e^{-2\kappa z} \quad (4)$$

For the further analysis, it is convenient, to insert the dimensionless variables

$$\tau=\omega_p t, \quad \varsigma=z\omega_p/v_{Te}, \quad \psi=E_l/E_{¿},$$

$$E_{¿}=\frac{\sqrt{3}}{2}E_m a_0{}^2, \quad E_m=\frac{mc\omega_p}{e}.$$

In these variables the equation (4) takes an form

$$\frac{\partial^2\psi}{\partial\tau^2}+\psi-\frac{\partial^2\psi}{\partial\varsigma^2}=-F(\tau/\tau_L)\cos\tau e^{-\alpha\varsigma}, \quad (5)$$

where. $\tau_L=\omega_p t_L$, $\alpha=\sqrt{3}v_{Te}/c$.

3. ANALYTICAL STUDY OF A PROBLEM

Thus, excitation of a Langmuir wave is described by Klein-Gordon equation with a right part relevant to a ponderomotive force on a second harmonic of laser radiation. A frequency of a second harmonic coincides with a plasma frequency.

Let's consider in the beginning a case of "cold" plasma. A Langmuir oscillation excitation in this case is described by an inhomogeneous equation of an oscillator. For simplicity we shall consider, that laser pulse has the symmetric profile. After a termination of a laser pulse action on plasmas the Langmuir oscillations with some structure of a field are excited. The plasma oscillations are concentrated in skin-layer. In case of a laser pulse with the Gaussian profile of a laser pulse temporal envelope of electric field amplitude depends on duration under a linear law.

The account of thermal energy of plasma electrons will decrease a plasma oscillations energy in a narrow skin-layer. The solution of the Klein - Gordon equation, describing this effect, has been obtained by a method of a Green function. Expression for a Green function looks like

$$G(\varsigma^*,\tau^*)=\frac{1}{2}\theta(\tau^*)\theta(\tau^*-\varsigma^*)\times\text{¿}$$

$$\text{¿¿}J_0(\sqrt{\tau^{*2}-\varsigma^{*2}\text{¿}}), \qquad (6)$$

¿

where $\theta(x)$ is Heviside function, $J_0(x)$ is the Bessel (cylindrical) function, $\zeta^*=\zeta-\zeta'$, $\tau^*=\tau-\tau'$. Accordingly, the solution of an inhomogeneous equation of Klein-Gordon can be noted as follows:

¿

$$\psi(\tau,\varsigma)=-\int_{-\infty}^{\tau} d\tau^* \int_{-\infty}^{\zeta} d\varsigma^* \theta(\tau^*-\varsigma^*)\cos(\tau-\tau^*)$$

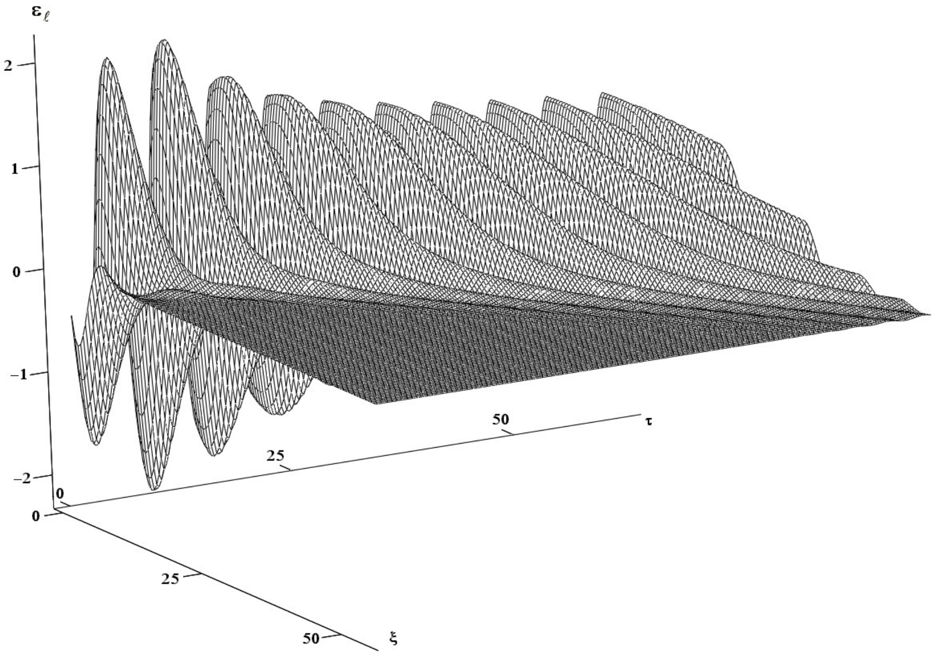
$$\text{¿}J_0(\sqrt{\tau^{*2}-\varsigma^{*2}\text{¿}})e^{-\alpha(\zeta-\varsigma^*)}F^*(\tau-\frac{\tau^*\text{¿}}{\tau_L}),$$

¿

$F^*=F/2$ (7)

4. ANALYTICAL AND NUMERICAL RESULTS AND DISCUSSIONS

Let's consider behaviour of a Langmuir wave amplitude at times essentially exceeding a pulse duration.
It is shown, at high times $\tau >> \varsigma_p 2$ ($\varsigma_p=\omega_p L/v_{Te}$, L is a plasma layer thickness) the plasma oscillation amplitude diminishes as $\tau^{-1/2}$.



The spatial and temporal distribution of a Langmuir wave electric field excited by laser pulse In dense plasma at following dimensionless parameters $t_L=12$, $\alpha=0.433$

For deriving of the complete pattern of nonlinear process of a Langmuir oscillation excitation by laser pulse in a dense plasma the Langmuir oscillation elect-ric field has been calculated numerically with help formula (7) at the following dimensionless parameters: $\tau_L=12,\quad \alpha=0.43$. The profile of laser pulse was simulated by function $F(\tau/\tau_L)=\cos\left(\frac{\pi}{2}\frac{\tau}{\tau_L}\right)$. For the laser with a wave length λ=1.05 μm to the indicated dimensionless parameters there correspond the following values of physical quantities: a plasma density $n_0=4.5\cdot10^{21}$ cm^{-3}, a plasma frequency $\omega_p=3.77\cdot10^{15}s^{-1}$, a plasma electron temperature T=32 keV. The figure illustrates a detailed pattern of a Langmuir wave excitation. It is visible, that the Langmuir wave disturbance is propagated into plasmas. The field in plasma has oscillation character with the amplitude that grows from a wave disturbance head to a plasma boundary. After wave disturbance front propagation past given space point the electric field oscillates with a plasma frequency. A dispersion spread of a Langmuir perturbation reduces in a diminution of a Langmuir oscillation maximum amplitude. In the dimensional unities a longitudinal electric field strength is determined by formula $E_l=\psi a_0^2\sqrt{3n_0/4}$ (V/cm), where n_0 is plasma density, a_0 is laser pulse dimensionless amplitude, ψ is efficiency coefficient of Langmuir wave excitation.

5. SUMMARY

Nonlinear mechanism of Langmuir wave excitation in dense plasma by intensive laser pulse has been investigated. A laser pulse that has frequency $\omega = \omega_p / 2$ propagate normally to boundary of semi-infinite plasma from vacuum. It is shown, this wave from source region propagate in plasma volume. In plasma a field have an oscillator character. Its amplitude increases from head of wave disturbance to plasma boundary. In each disturb point of space this field oscillate on plasma frequency.

The Langmuir disturbance dispersion reduction ensures the Langmuir oscillation maximum amplitude decreasing. The longitudinal electric field magnitude have been determined by relation

$$E_l = \psi a_0^2 \sqrt{3n_0 / 4} \text{ (V/cm)},$$

. It is important note, that in recent article [3] have place direct experimental evidence of accelerated electron bunches separated by half the period of the laser light at irradiation of thick solid targets by laser beam at relativistic intensities.

The work was supported in part by INTAS project #01-233 and Foundation of Fundamental Researches of the Ukraine project # 02.07/213.

REFERENCES

1. V.A. Balakirev, V.I. Karas`, I.V. Karas`, and V.D. Levchenko. Plasma wake-field excitation by relativistic electron bunches and charged particle acceleration in the presence of external magnetic field // *Laser and Particle Beams (19)* . 2001, p. 597-604.

2. V.A. Balakirev, V.I. Karas`, I.V. Karas`. Charged particle Acceleration by an Intense Ultra-short Electromagnetic Pulse Excited in a Plasma by Laser Radiation or by Relativistic Electron Bunches // *Plasma Phys. Rep (28).* 2002**,** p.125-140.

3. S.D. Baton, J.J. Santos, F. Amiranoff, H. Popescu , L.Gremillet, M. Koenig, E. Martinolli, Guilbaud, C.Rousseaux, Lr Gloahec., T. Hall, D. Batani, E. Perelli, F. Scianitti, T.E. Cowan. Evidence of Ultra-short Electron Bunches in Laser-Plasma Interactions at Relativistic Intensities // *Phys. Rev. Lett. (91).* 2003, p. 105001-1 – 105001-4.

4. S.V. Bulanov, T.Zh. Esirkepov, J.Koga, T.Tajima, and D. Farina. Concerning the Maximum Energy of Ions Accelerated at the Front of a Relativistic Electron Cloud Expanding into Vacuum // *Plasma Phys. Rep. (28).* 2002, 125-140.

5. M.J.Hogan, C.E.Clayton, C.Huang, P.Muggli, S.Wang, B.E.Blue, D.Walz, K.A.Marsh, C.L.O`Connel, S.Lee, R.Iverson, F.-J.Decker, P.Raimond , W.B.Mori, T.C.Katsouleas, C.Joshi, and R.H.Siemann. Ultra-relativistic-Positron–Beam Transport through Meter-Scale Plasmas // *Phys. Rev. Lett. (78).* 2003, p. 205002-1 - 205002-4.

6. Y.Kitagawa, T.Matsumoto, T.Minamihata, K.Sawai, K. Matsuo, K. Mima, K. Nishihara, H. Azechi, K.A. Tanaka, H. Takabe, and S. Nakai. Beat-Wave Excitation of Plasma Wave and Observation of Accelerated Electrons // *Phys. Rev. Lett. (68).* 2003, p. 48-51.

7. P. Sprangle, J.R. Penano, B. Hafizi, R.F. Hubbard, A. Ting, D.F. Gordon, A. Zigler, T.M.Jr. Antonsen. GeV acceleration in tapered plasma channels. *Physics of Plasmas (9).* 2002, p. 2364-2370.

ВОЗБУЖДЕНИЕ ЛЕНГМЮРОВСКИХ КОЛЕБАНИЙ В ПОЛУОГРАНИЧЕННОЙ ПЛОТНОЙ ПЛАЗМЕ ЛАЗЕРНЫМ ИМПУЛЬСОМ

В.А. Балакирев, И.В. Карась, В.И. Карась, Я.Б. Файнберг, А.П. Толстолужский

Исследован нелинейный механизм возбуждения ленгмюровских волн в плотной плазме интенсивным лазерным импульсом с частотой $\omega = \omega_p / 2$ (где ω_p - электронная плазменная частота).

ЗБУДЖЕННЯ ЛЕНГМЮРОВСЬКИХ КОЛИВАНЬ У НАПІВОБМЕЖЕНІЙ ЩІЛЬНІЙ ПЛАЗМІ ЛАЗЕРНИМ ІМПУЛЬСОМ

В.А. Балакірев, І.В. Карась, В.І. Карась, Я.Б. Файнберг, О.П. Толстолужський

Досліджено нелінійний механізм збудження ленгмюровських хвиль у щільній плазмі інтенсивним лазерним імпульсом з частотою $\omega = \omega_p / 2$ (де ω_p - електронна плазмова частота).