RESONANCE EXCITATION AND FREQUENCY UP-CONVERSION OF PLASMA OSCILLATIONS UPON THE OPTICAL BREAKDOWN OF A THIN FILM

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We study the spatiotemporal evolution of the field and plasma during the optical breakdown process induced by *p*-polarized laser radiation in a thin gaseous layer. The computer simulation of the process based on the solution of the vector wave equation for the slow time-varying field amplitude and the known expression for the tunnel ionization rate is carried out with taking into account the spatial dispersion caused by the thermal motion of electrons. It is found that generation of the plasma waves during the transition through the plasma resonance points in the layer affects strongly the dynamics of breakdown process and the spectrum of reflected and transmitted radiation.

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1. INTRODUCTION

The resonance phenomena accompanying the optical-induced breakdown of the small-scale bodies has drawn attention in recent years due to its potentialities in different nano-plasma applications. They may be used, for example, for the effective energy pumping in the small atomic clusters [1,2], tuning and generation of electromagnetic radiation by the axicon-created plasma filament [3-5], and conversion of the scattered wave spectrum in the breakdown process in thin films [6,7]. The last of the mentioned problem was solved formerly only within the framework of a simple model that considered the homogeneous and cold plasma layer with sharp boundary, without spatial dispersion taken into account. This work aims at the investigation of the plasma and field dynamics during the optical breakdown of a film (thin layer of a dense gas) under condition when the plasma oscillation spectrum is determined essentially by the spatial dispersion caused by electron thermal motion. In this case, the excitation of plasma waves results in both the electric field and field-created plasma occur to be inhomogeneous that affects greatly the dynamics of breakdown and the spectrum of reflected and transmitted waves.

2. FORMULATION OF THE PROBLEM AND BASIC EQUATIONS

Consider a plane *p*-polarized electromagnetic wave of frequency ω incident at an angle θ_0 on a homogeneous gas layer occupying the region $0 < x < d$. The thickness of the layer is supposed to be small as compared to the wavelength: $k_0 d << 1$ $(k_0 = \omega / c)$. The magnetic field of the wave has only one component which is given by the real part of complex field

$$B_z^{(i)} = B_0 \exp(-i\omega t + ik_0 \cos\theta_0 x + ik_0 \sin\theta_0 y)\,. \quad (1)$$

The components of complex electric field of the incident wave are

$$E_x^{(i)} = -B_0 \sin\theta_0\,, \quad E_y^{(i)} = B_0 \cos\theta_0\,. \quad (2)$$

The electric field causes the tunnel ionization of atoms in the layer and produces, as a result, a time-varying (and inhomogeneous in general case) plasma with the density $N(x,t)$. We describe this process based on the known model expression for the field-period-averaged tunnel ionization rate of hydrogen atoms

$$\frac{\partial N}{\partial t} = 4\left(\frac{3E_a}{\pi\,|\mathbf{E}|}\right)^{1/2} \Omega\ (N_g - N)\exp\left(-\frac{2E_a}{3|\mathbf{E}|}\right). \quad (3)$$

Here $E_a = 5.14 \times 10^9$ V/cm and $\Omega = 4.16 \times 10^{16}$ s^{-1} are the atomic units of electric field and frequency, respectively, N_g is the density of atoms before ionization, $\mathbf{E}$ is the complex amplitude of electric field in plasma. Eq. (3) is valid if the following inequality are fulfilled

$$|\mathbf{E}| << E_a\,, \quad \frac{e^2}{m\omega^2}|\mathbf{E}|^2 >> W_i\,, \quad \omega << \Omega\,,$$

where W_i is the energy of ionization.

The basic wave equation for the vector of slowly varying amplitude $\mathbf{E}$ with the spatial dispersion and collisionless damping taken into account can be written as

$$\frac{2i}{\omega}\frac{\partial \mathbf{E}}{\partial t} + \delta^2 \nabla(\nabla \cdot \mathbf{E}) + \varepsilon \mathbf{E} - \frac{c^2}{\omega^2}[\nabla \times [\nabla \cdot \mathbf{E}]] + \hat{T}\mathbf{E} = 0\,. \quad (4)$$

Here $\varepsilon = 1 - \dfrac{\omega_p^2}{\omega(\omega + i\nu)} = 1 - \dfrac{N}{N_c(1 + i\nu)}$ is the complex permittivity of the cold plasma, $N_c = m\omega^2 / 4\pi e^2$ is the critical density, ν is the electron collision frequency, $\delta = \sqrt{3}\, V_T / \omega$, V_T is the thermal velocity of electrons, $\hat{T}$ is the operator describing collisionless (Landau) damping, for which we use the simplest model expression

$$\hat{T}\mathbf{E} = -ia\delta^2 \nabla(\nabla \cdot \mathbf{E})\,, \quad a = \text{const.}$$

It is supposed that $\nu << \omega$, $V_T << c$, $a < 1$.

The phenomena of resonance excitation of both the induced and free (natural) plasma oscillations in the layer are associated with the normal (respect to layer boundaries) component of electric field E_x. The equation for this component can be obtained (as generalization of analogues procedure in [6, 7]) from Eq. (4). For the thin layer here considered this equation has the form

$$\frac{2i}{\omega}\frac{\partial E_x}{\partial t} + \varepsilon E_x + \delta^2 (1 - ia)\left(\frac{\partial^2 E_x}{\partial x^2} - \sin^2\theta_0 E_x\right) = F\,, \quad (5)$$

where

$$F = \sin\theta_0 \left(\frac{k_0 d \,\mathrm{tg}\theta_0}{2} \left(\frac{1}{\omega} \frac{\partial \overline{E}_x}{\partial t} - i\overline{E}_x \right) - B_0 \right), \quad (6)$$

$\overline{E}_x = d^{-1} \int_0^d E_x dx$ is the average field at the interval $(0, d)$.

The tangential (parallel to the boundaries) components of electric (E_y) and magnetic (B_z) fields in the thin layer can be approximated as constants

$$E_y = B_0 \cos\theta_0 + i k_0 d \sin\theta_0 \overline{E}_x, \quad (7)$$

$$B_z = B_0 + \frac{1}{2} i k_0 d \,\mathrm{tg}\theta_0 \overline{E}_x. \quad (8)$$

The equation (5) has need of some boundary conditions at the edges of the interval $(0, d)$. These conditions can be obtained, if one specifies the nature of electron interaction with the plasma boundary. We take here the conventional condition of vanishing the normal component of electron current at the boundary that corresponds to the "mirror reflection" of electrons. In hydrodynamics approximation we used here it leads to the conditions (at $x = 0, d$)

$$\frac{i}{\omega} \frac{\partial E_x}{\partial t} + E_x = -\sin\theta_0 \left(B_0 + \frac{i}{2} k_0 d \,\mathrm{tg}\theta_0 \overline{E}_x \right). \quad (9)$$

3. RESULTS OF COMPUTER SIMULATION

The equations (3), (5), (6) with boundary condition (9) and initial condition (at $t = 0$)

$$E_x = -\sin\theta_0 B_0, \quad N = 0, \quad (10)$$

were solved numerically under parameter values $k_0 d = 0.05$, $\omega / \Omega = 0.04$, $B_0 / E_a = 0.05$, $\theta_0 = 45^{\circ}$, $k_0 \delta = \sqrt{3} V_T / c = 0.002$, $N_g / N_c = 1.5$, $a = 0.1$. These parameter values correspond to the laser radiation with the wavelength $\lambda \approx 1 \mu\mathrm{m}$, the intensity $I \approx 0.75 \times 10^{14}$ W/cm^2, and the gas pressure $p \approx 50$ atm. The results of calculations are presented in Figs.1-4.

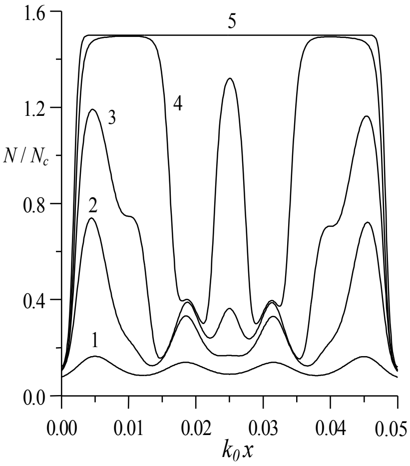

Fig.1. Plasma density profiles at different time instants. Curves 1-5 correspond to the values ωt = 75, 100, 105, 110, 125, respectively

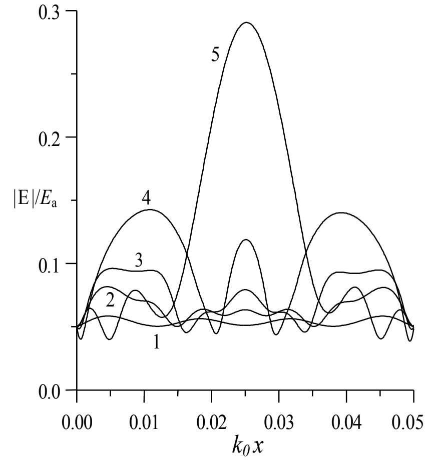

Fig.2. Electric field amplitude distributions at the same time instants as in Fig.1

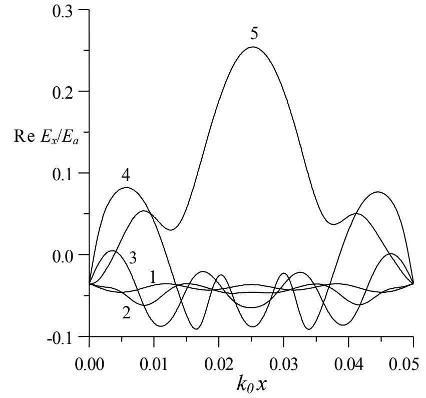

Fig.3. Real part of the normal component of the electric field complex amplitude at the same time instants as in Figs.1,2

Figs.1-3 show the spatiotemporal evolution of the plasma density and electric field; curves 1-5 on all figures present corresponding space distributions at the instants of dimensionless time ωt = 75, 100, 105, 110, 125, respectively. At the initial stage (curves 1) the quasi-periodical plasma-field structure is forming. Its space period corresponds probably to the plasma-wave mode whose excitation occurs to be optimal at the given rates of dissipation and plasma creation. The wave amplitude is maximal near the boundaries (where the excitation take place) and decreases deep into the layer due to collisionless damping. The subsequent evolution has rather complicated character that is caused by the excitation and interference of several free plasma-waves modes with different time and space periods. These processes are especially intensified at the time of transition through the plasma resonance points and results in, at some intermediate stage (curves 2-4), the strongly inhomogeneous plasma profiles. At the last stage of the process, the gas is almost fully ionized, and the quasi-homogeneous plasma profile with sharp boundary (similar to curve 5 at Fig.1) is formed. Note that the field distribution at the time instant corresponding to curve 5 ($\omega t = 125$) is far from the stationary state since the field contains a slowly damping free-oscillation component with maximum at the center of the layer (curves 5 at Figs.2,3).

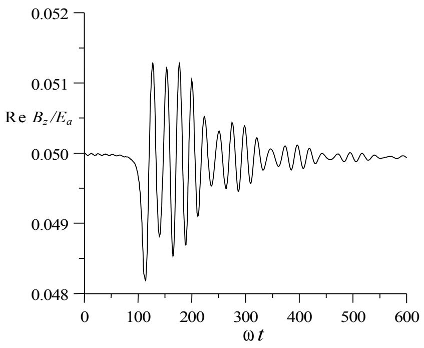

Fig.4. Time dependence of the real part of magnetic field complex amplitude

Fig.4 shows the time dependence of the real part of the magnetic field $\mathrm{Re}\,B_z$ within the layer and at its boundaries. The oscillating character of this dependence indicates that the field spectrum contains several distinguished frequency components (main frequency ω and some frequencies near the maximum plasma frequency $\omega_{p\max} \approx 1.22\omega$, corresponding to the free plasma-wave modes). It is evidently that the spectrum of the scattered (reflected and transmitted) radiation contains these frequency components also, and thus the considered breakdown phenomenon must be followed by the generation of a number new (in our case blueshifted) spectral components.

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РЕЗОНАНСНОЕ ВОЗБУЖДЕНИЕ И ПРЕОБРАЗОВАНИЕ ЧАСТОТЫ ПЛАЗМЕННЫХ КОЛЕБАНИЙ В ПРОЦЕССЕ ОПТИЧЕСКОГО ПРОБОЯ ТОНКОЙ ПЛЕНКИ

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Исследуется пространственно-временная эволюция поля и плазмы в процессе оптического пробоя тонкой газовой пленки *p*-поляризованным лазерным излучением. Исходная система уравнений включает в себя векторное волновое уравнение для медленной временной огибающей поля, материальное уравнение для плотности тока, учитывающее пространственную дисперсию, и выражение для скорости туннельной ионизации атомов газа. Проведенное компьютерное моделирование показало, что эффект генерации собственных плазменных колебаний в процессе перехода плотности плазмы через точку плазменного резонанса сильно влияет на динамику процесса пробоя и спектры отраженного и прошедшего через плазменный слой излучения.

РЕЗОНАНСНЕ ЗБУДЖЕННЯ ТА ПЕРЕТВОРЕННЯ ЧАСТОТИ ПЛАЗМОВИХ КОЛИВАНЬ У ПРОЦЕСІ ОПТИЧНОГО ПРОБОЮ ТОНКОЇ ПЛІВКИ

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Ми вивчаємо просторово-часову еволюцію поля та плазми у процесі оптичного пробою, що індукований лазерним випромінюванням з р-поляризацією у тонкому газовому шарі. Комп'ютерне моделювання процесу засновано на розв'язанні векторного хвилевого рівняння для амплітуд поля, які повільно змінюються, та відомих виразів для швидкості тунельної іонізації, що проведено з урахуванням просторової дисперсії, яка викликана тепловим рухом електронів. Знайдено, що генерація плазмових хвиль протягом проходження через точки плазмового резонансу у шарі сильно впливає на динаміку процесу пробою та спектр відбитого та проникного випромінювання.