NONLINEAR DYNAMICS OF SHORT LASER PULSES IN PLASMA PRODUCTION PROCESSES

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The report is devoted to the investigation into the dynamics and structure of the field and field-created plasma in optical-field-induced ionization processes produced by the laser pulse of high intensity 10^{14}-10^{18} W/cm^2. Based on the theoretical analysis and computer simulation, we have found and analyzed three groups of new nonlinear effects inherent in the ionization processes considered and not taking place for the so called "focusing nonlinearity" mechanisms (ponderomotive, relativistic, etc.).

1. The first group of effects concerns the time-spectrum transformation of radiation in the ionization processes. We have studied the nonlinear spatio-temporal evolution of the focused fs laser pulse and the plasma produced by the pulse itself due to tunneling gas ionization. The computer simulation on the basis of exact 2D wave equation [1] allowed to predict and describe the high self-blueshifting effect and formation of short leading peaks of the field (half-wave ionizing "leaders").

The pulse electric field $\mathbf{E} = \mathbf{y}_0 E(x,z,t)$ and plasma density $N(x,z,t)$ were described by the 2D wave equation and equation for the ionization growth rate

$$\frac{\partial^2 E}{\partial x^2}+\frac{\partial^2 E}{\partial z^2}-\frac{1}{c^2}\frac{\partial^2 E}{\partial t^2}=\frac{4\pi e^2}{mc^2}NE, \qquad \frac{\partial N}{\partial t}=4\Omega(N_m-N)\frac{E_a}{|E|}\exp\left(-\frac{2E_a}{3|E|}\right), \qquad (1)$$

Here x and z are the transverse and longitudinal (with respect to the pulse propagation direction) Cartesian coordinates, respectively; $E_a=me^5/\hbar^4=5.14\ 10^9$ V/cm is a characteristic atomic field, $\Omega=me^2/\hbar^3=4.16\ 10^{16}$ s^{-1}, N_m is the gas atom density. When using the equations (1), the conditions of the ionization rate instantaneously following the optical field oscillations ($e^2E_0^2/2m\omega^2 >> \hbar\,\Omega$, $\Omega >> \omega$), and the electron collision frequency ν small enough ($\nu << \omega$, $\nu << N_c^{-1}\,\partial N/\partial t$) are supposed to be fulfilled; $N_c = m\omega^2/4\pi e^2$; ω and E_0 are a characteristic frequency and an amplitude of the field, respectively.

At the time $t = 0$, the initial conditions were chosen so that the wave packet, in the absence of ionization, moves to $+z$ direction, forming at some time $t = t_0$ the focused pulse of wavelength λ, with some given z-envelope $g(z)$ and Gaussian transverse profile: $E(x,z,t_0) = E_0 \sin(kz)\, g(z) \exp(-x^2/2a^2)$. Here a is a focal spot radius; $k=2\pi/\lambda = \omega_0/c$, ω_0 is the initial (undisturbed) field frequency.

Figs. 1,2 present (using hereafter the dimensionless variables $z \to kz$, $t \to \omega_0 t$, $E \to 3E/2E_a$) the results of computer simulation on the basis of equation set (1) for the 10 fs, 1 μm, 80MW rectangular laser pulse, focused at $f/7$ optics to the vacuum peak intensity of 10^{15} W/cm^2 (a = 1.6 μm) into a 5 atm H_2 gas. Fig.1 demonstrates a sizable upshift of the time-spectrum maximum ($\Delta\omega/\omega \cong 42\%$) of the pulse as a whole at the axis after passing the ionizing region. The maximum plasma density in the example considered achieves the value $N_{max} = 0.67\ N_m = 0.09\ N_{c0}$, defined by the ionizing action of an ultra-short high-amplitude "leader" which forms at the leading edge of the pulse (see Fig. 2). The leader, consisting of only one or two half-wave, propagates continuously in the region of both comparatively small average plasma density N and high value of its growth rate $\partial N/\partial t$. As a result the leader is only slightly subjected to defocusing in plasma but undergoes a sharp frequency upshifting. As we can see from the plots of E versus t at x=0 (Fig. 2), during and after passing the focal region, the first wave period of the pulse is $T \approx (1/2\text{-}1/3)T_0$, where $T_0 = 2\pi/\omega_0$.

2. Effects of the second group consist in formation of the self-localized plasma waveguides with a free boundary, that confine the electromagnetic wave and can provide the directed transfer of radiation and ionization for a long distance. We have found two types of possible self-channeling ionization structures : (i) the sharp-bounded wide plasma waveguide supporting, at saturable ionization, the fast wave with a slight leakage; (ii) the thin overcritical plasma layer, supporting the slow surface wave.

(i) The leaking mode self-channeling is due to a strong reflection of the trapped wave by the sharp boundaries of plasma channel. This was considered recently, based on the paraxial long pulse approximation [2]. Here we demonstrate that this effect takes place for the ultra-short (few-optical-cycle) pulse too. In Figs. 3,4, are shown the results of the above set (1) computation for the 10fs, 1μm Gaussian laser pulse, focused at *f*/3 to the higher peak intensity (6 10^{15} W/cm^2), providing the complete ionization at the same gas pressure. We can see that a long plasma channel is created in this case (Fig. 3). The full channel length is 65μm that is 22 times more than the Rayleigh length $z_R=kb^2$ (12 z_R before the focus point and 10 z_R behind one). The transverse structure of the optical field is well localized in the plasma channel (Fig.4), indicating that the radiation losses of leaking mode are rather small.

(ii) The surface wave self-channeling was found to occur at gas breakdown by two crossing plane waves. Corresponding initial problem for a *p*-polarizing wave with the given longitudinal wave number k_z in the self-consistent x-periodical plasma structure $N(x,t)$ was solved by the computer simulation. In this simulation, the slowly time-varying field amplitudes $E_{x,z}\,(x,t)$ and field frequency $\omega(t)$ were defined at each time instant t respectively as the eigenfunctions and eigenvalue for the stationary 1D wave equation in plasma. The evolution equations for both the plasma density (the second of (1)) and the quasi-monochromatic field energy (with the ionization and collision losses taken into account) were used. The Fig. 5 illustrates (in the same dimensionless variables) the time evolution of the field amplitude E_x (solid curves) and density $n=N/N_{c0}$ (asterisks) distributions for the parameter values, corresponding to the breakdown of 60 atm H_2 by the 1 μm radiation with the initial maximal intensity 3 10^{14} W/cm^2 at k_z =0.95(ω_0/c). At some stage of the process, a thin (slowly expanding) plasma waveguide with the density $N>N_c$ arises, and the field takes the form of the surface wave localized close to its boundaries. The wave frequency ω at this stage is found to decrease and the wave turns into the slow one (at t = 63.91 we found $\omega = 0.82\omega_0$, v = ω / k_z = 0.86 c).

3. The third group includes the effects caused by the plasma-resonance ionization (PRI) instability [3]. The laser field amplitude and plasma are found to be unstable in plasma creation process relative to spatial modulation in the direction of laser electric field with the period L small as compared to the wavelength λ . In a solid or dense gas the process, at the nonlinear stage of instability, goes on in the sharpening regime and leads to the formation of long lifetime microstructure with electric field concentrated into thin plasma layers. Some results of computer simulation of this process, in frames of initial problem for the plane wave ($k_z= \omega_0 /c$) in x-modulated medium, are presented in Figs. 6 at the wave intensity 10^{14} W/cm^2 and above values of the wavelengths and gas pressure. The described microfilamentation can provide the transparency of the ionization region; it is possible that this was realized in the recently published experiments [4] on transmission of 30 fs intense laser pulse through solid-density laminar plasma.

The effects considered change drastically the characteristics of plasma-field interaction and they are of importance for applications connected with the creation of dense laser plasma, such as the diagnostics and conversion of laser pulse spectra, the creation of x-ray lasers, particle acceleration in plasma, and probably the passage of high-intensity laser pulses through dense ionizable matter.

Acknowledgement

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References

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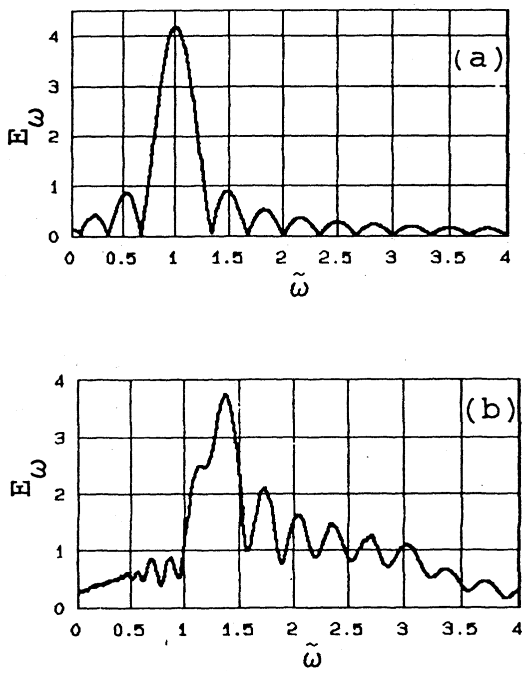

Fig. 1. Time spectra of the electric field (in arbitrary units) versus $\tilde{\omega} = \omega / \omega_0$ at the axis points (a) z=-780, (b) z=60.

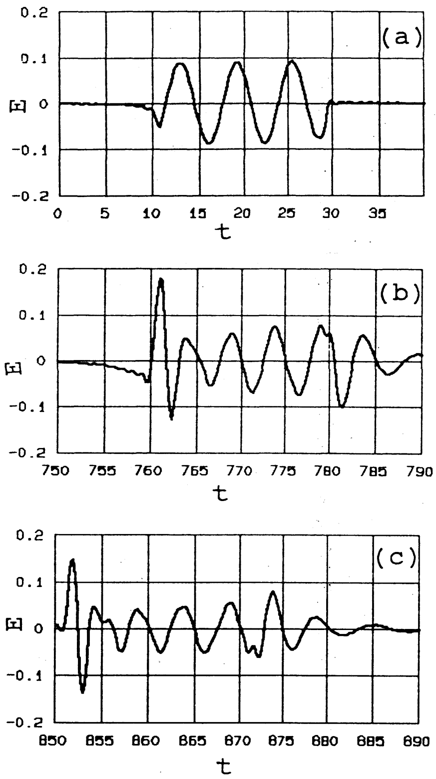

Fig. 2. Plots of E versus t at the axis points (a) z = -780, (b) z = -30, (c) z =60.

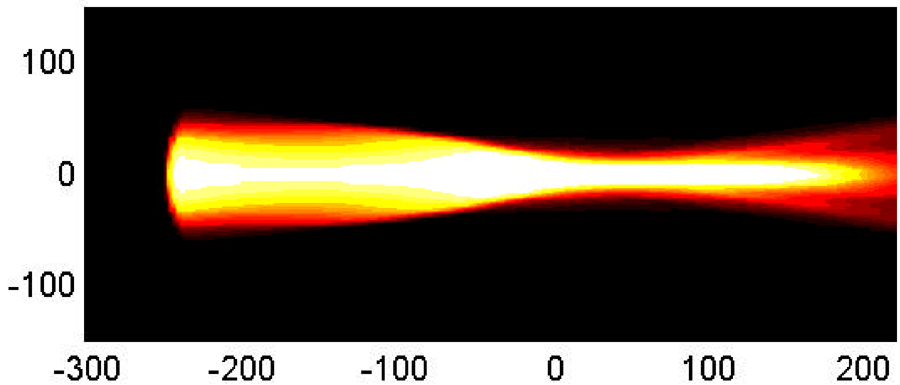

Fig. 3. Plasma density distribution *N(x,z)* after pulse passing.

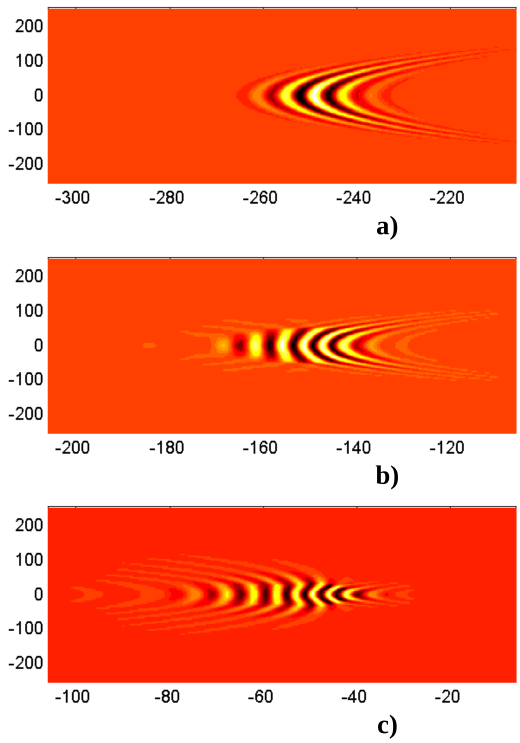

Fig. 4. Spatio-temporal evolution of the electric field $E(x,z,t)$;
(a)-(c) corresponds to t=0,100 and 200 respectively.

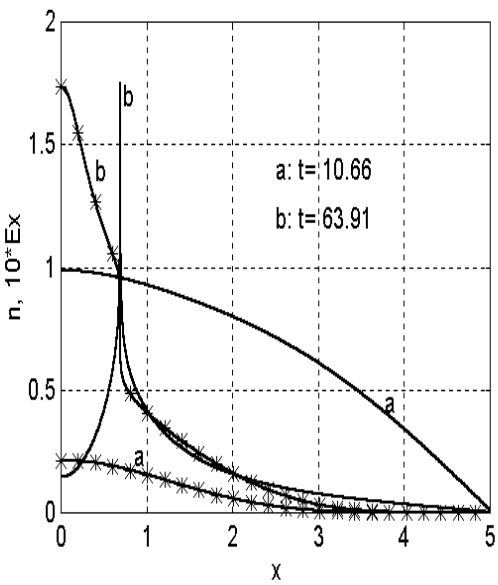

Fig. 5. Transverse field component $E_x(x)$ (solids) and plasma density $n(x)=N/N_{c0}$ (asterisks) at two instants of time.

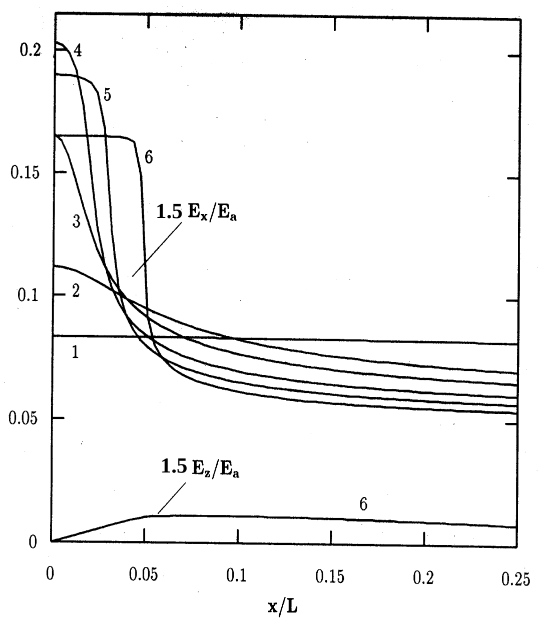

Fig. 6. Transverse $E_x(x)$ and longitudinal $E_z(x)$ fields at various instants of time; the curves 1-6 corresponds to t =0, 336, 362, 384, 464 and 1136, respectively. The period of transverse modulation is $L = \lambda/3$.