

Self-modulated Laser Wakefield in Ionizing Gases.

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Abstract

Wakefield generation during the intensive laser pulse propagation in the gas being ionized is under consideration. At the very entrance of the gas the wakefield is generated by the ionization mechanism [1] and becomes a seed for self-modulation instability. Further (with deeper penetration into the gas) a strong 3-D ionization refraction at the very leading edge of the laser pulse leads to strong deformation of the temporal-spatial laser pulse profile. The latter becomes almost abrupt and effectively generates plasma waves at the moving ionization front. Such plasma waves turn up as a seed for self-modulation instability and bring the wakefield generation to the highly excited self-modulation stage with large magnitude of the accelerating electric field. The latter starts at the laser pulse penetration depth less than Rayleigh length and takes place along the comparatively large distance in the gas.

Introduction

There are opinions why the use of a uniform gaseous medium to generate large amplitude plasma waves by high-intensity laser pulses has important advantages compare to the preformed plasma. Firstly at some conditions the rapid ionization through optical field ionization (OFI) can produce a plasma with an almost uniform density [2]. Secondly an ionization front created by OFI in a leading front of the laser pulse is itself a source of plasma waves [1]. The latter in turn could be a seed for self-modulation instability of the mostly intensive part of the laser pulse. From these points of view neutral gas is attractive to use in novel laser-plasma accelerator schemes (see for example [3]). A negative feature of such use which typically treated as the most serious one is ionization-induced defocusing (IID) (see for example [4]). First of all it makes comparatively high demands of the gas-vacuum boundary (laser-gas interface) i.e. the boundary has to be narrow enough (see for example [5,6]). In the case of comparatively low power laser beams IID shortens the laser pulse propagation in the matter being ionized by the refraction of the focused laser radiation at the strongly localized plasma produced by OFI. If the laser power P is well above critical power for relativistic self-focusing P_c ($P > 10 P_c$) the laser pulse breaks through the ionized matter along the distance much larger than Rayleigh length z_R [5]. However such high power leads to 1) plasma wave breaking (which is detected by observation of high plasma wave harmonic generation), 2) the distortions of the laser pulse trace in the gas which is accompanied by the pulse splitting, 3) the rather unstable plasma channel length [5]. In turn these features makes the process of electron acceleration rather unstable.

In the present paper we describe the wakefield generation in the regime of low power ($P < P_c$) laser pulse propagation in gas being ionized. Comparatively low peak intensity of the pulse enables to neglect the influence of the stimulated Raman scattering on the laser pulse propagation and wakefield generation (see for example [7]). We discuss comparatively long laser pulse when the pulse duration is much larger compare to the plasma wave period and resonance condition [8] doesn't hold. Such laser pulse is suitable for self-resonant wakefield excitation (selfmodulation instability) [9]. Seed for this instability can be produced by the laser pulse which temporal profile is pertinently deformed with sharp enough leading edge [10]. Long pulse with initially smooth temporal profile can generate wakefield through the selfmodulation instability at $P < P_c$ [11]. But such mechanism needs long enough laser pulse path in the plasma (much longer than z_R) till the pulse temporal profile becomes sharp enough [10].

In the present treatment the laser pulse undergoes IID in accordance with conventional point of view. Nevertheless at the very entrance of the gas (at distances $z < z_R$ before the above defocusing) refraction of the laser pulse on the plasma created by OFI increases the intensity of the pulse on the beam axis. Simultaneously the pulse undergoes IID in the leading edge. In turn the laser pulse temporal profile becomes steeper and can effectively generate wakefield itself in accordance with [8]. Further intensive laser pulse core undergoes self-

modulation instability with the pulse penetration into the gas. As a result a regular wakefield is generated along the distance of about several tenth of z_R . It is shown that the electron energy gain from plasma wave electric field could be about 1 GeV.

Basic equations and initial conditions.

Further it will be demonstrated that starting from the moderate laser pulse peak intensities (when $a_0 = |e|E_0/m\mathbf{w}_0c \ll 1$, where $e(m)$ is the electron charge (mass), c the speed of light, \mathbf{w}_0 (E_0) the laser pulse frequency (electric field peak value)) the peak intensity does not increase to the relativistically high values. Because of this we use the following system of equations for slowly varying laser pulse vector amplitude $\mathbf{a} = |e|\mathbf{E}/m\mathbf{w}_0c$, scalar dimensionless function \mathbf{f} (potential) and electron density n_e (compare with [6])

$$\begin{cases} 2\mathbf{w}_0c \frac{\mathcal{I}\mathbf{a}}{\mathcal{I}z} - 2ic^2 \frac{\mathcal{I}^2\mathbf{a}}{\mathcal{I}z\mathcal{I}\mathbf{x}} - ic^2\Delta_{\perp}\mathbf{a} + i\mathbf{w}_p^2 \left(\frac{n_e}{N} - \frac{1}{4}|\mathbf{a}|^2 \right) \mathbf{a} = \frac{\Gamma_2\mathbf{w}_0}{4n_c} \mathbf{a}^* - \mathbf{a} \frac{2\mathbf{w}_0}{|\mathbf{a}|^2} \sum_{k=0}^{Z-1} \frac{\Gamma_0^{(k)}}{n_c} \frac{U_k}{mc^2}, \\ k_p^2 \left(\frac{n_e}{N} - \frac{1}{4}|\mathbf{a}|^2 \right) = k_p^2 + (\Delta_{\perp} - k_p^2)\mathbf{f} + \int_{+\infty}^{\mathbf{x}} \left(\mathbf{f} + \frac{1}{4}|\mathbf{a}|^2 - \text{Re} \left[(\mathbf{a}^*)^2 \frac{\Gamma_2}{8\Gamma_0} \right] \right) \frac{\mathcal{I}k_p^2}{\mathcal{I}\mathbf{x}} d\mathbf{x}, \\ (\Delta_{\perp} - k_p^2) \frac{\mathcal{I}^2\mathbf{f}}{\mathcal{I}\mathbf{x}^2} + k_p^2(\Delta_{\perp} - k_p^2)\mathbf{f} - \frac{\mathcal{I}\ln N}{\mathcal{I}r} \frac{\mathcal{I}^3\mathbf{f}}{\mathcal{I}r\mathcal{I}\mathbf{x}^2} = \frac{k_p^2}{4}(\Delta_{\perp} - k_p^2)|\mathbf{a}|^2 + \\ - k_p^2 \int_{+\infty}^{\mathbf{x}} \left(\mathbf{f} + \frac{1}{4}|\mathbf{a}|^2 - \text{Re} \left[(\mathbf{a}^*)^2 \frac{\Gamma_2}{8\Gamma_0} \right] \right) \frac{\mathcal{I}k_p^2}{\mathcal{I}\mathbf{x}} d\mathbf{x}, \end{cases} \quad (1)$$

where $|e|N(r, \mathbf{x}) = -\frac{|e|}{c} \int_{+\infty}^{\mathbf{x}} \Gamma_0(r, \mathbf{x}') d\mathbf{x}'$ is the slowly varying charge density of ions which are considered

immobile, $\mathbf{w}_p^2(r, \mathbf{x}) = 4pe^2N(r, \mathbf{x})/m$, $n_c = m\mathbf{w}_0^2/4pe^2$ the critical density, $k_p^2 = \mathbf{w}_p^2/c^2$, $\Delta_{\perp} = \frac{1}{r} \frac{\mathcal{I}}{\mathcal{I}r} \left(r \frac{\mathcal{I}}{\mathcal{I}r} \right)$ the transverse part of the Laplace operator, $r = |\mathbf{r}|$, \mathbf{r} is perpendicular to the laser beam axis Oz , $\mathbf{x} = z - ct$. Notice that the slowly varying plasma wave electric field with longitudinal $E_{p,z}$ and radial $E_{p,r}$ components and azimuthal component $B_{p,j}$ of the magnetic field are coupled with potential \mathbf{f} by the following relations

$$\frac{eE_{p,z}}{mc^2} = \frac{\mathcal{I}\mathbf{f}}{\mathcal{I}\mathbf{x}}, \quad \frac{eE_{p,r}}{mc^2} - \frac{eB_{p,j}}{mc^2} = \frac{\mathcal{I}\mathbf{f}}{\mathcal{I}r}.$$

System (1) is accompanied by the following equations for zeroth (Γ_0) and the second (Γ_2) harmonics of the electron ionization rate ($\Gamma_j \equiv \sum_{k=0}^{Z-1} \Gamma_j^{(k)}$, $j = 0, 2$)

$$c \frac{\mathcal{I}n_0}{\mathcal{I}\mathbf{x}} = \Gamma_0^{(0)}, \quad c \frac{\mathcal{I}n_k}{\mathcal{I}\mathbf{x}} = \Gamma_0^{(k)} - \Gamma_0^{(k-1)}, \quad c \frac{\mathcal{I}n_Z}{\mathcal{I}\mathbf{x}} = -\Gamma_0^{(Z-1)}, \quad \Gamma_0^{(k)} \equiv W_k n_k, \quad k = 1, \dots, Z-1, \quad \Gamma_0^{(0)} \equiv W_0 n_0, \quad (2)$$

where $\Gamma_j^{(k)}$ is j -th harmonic of the rate of ionization of ion with charge $k \times |e|$ producing an ion with charge $(k+1) \times |e|$, Γ_j is j -th harmonic of the total ionization rate from any atomic shells, Z the nuclear charge, W_k is the probability of the tunneling ionization of an ion in the k -th ionization state per unit time ($k=0$ corresponds to a neutral atom), n_k is the density of such ions, and n_0 is the density of neutral atoms. The probability W_k is described by the ADK formula [12] which is averaged over the laser pulse period:

$$W_k(E) = \mathbf{w}_{at} \sqrt{3} \left(\frac{e^1}{\mathbf{p}} \right)^{3/2} \frac{(k+1)^2}{n^{4.5}} \left[4 \cdot e^1 \frac{(k+1)^3}{n^4} \frac{E_{at}}{|E|} \right]^{2n-1.5} \exp \left(-\frac{2}{3} \frac{(k+1)^3}{n^3} \frac{E_{at}}{|E|} \right), \quad (3)$$

where $E = |\mathbf{E}|$, $E_{at} = 5.142 \times 10^9$ V/cm is the atomic electric field strength, $n^* = (k+1) \sqrt{U_H/U_k}$, U_H is the potential for ionization of a hydrogen atom from the ground state, $\mathbf{w}_{at} = 4.1 \times 10^{16} \text{ s}^{-1}$ is the atomic frequency, and $e^1 \approx 2.72$ is the base of natural logarithms. The relation between the second and zeroth harmonics strongly depends on the polarization of the laser electric field \mathbf{E} . For circularly polarized electric field $\Gamma_2 \equiv 0$. For

linearly polarized \mathbf{E} the ratio $\Gamma_2/\Gamma_0 \equiv 2\mu$ is approximately constant in time and slowly depending on the sort of gas [1]. Below we discuss helium and $\mu = 0.78$.

The boundary and initial conditions for (1)-(3) are the following: Gaussian in space and time laser pulse

$$\mathbf{a}(z=0, \mathbf{r}, \mathbf{x}) = \mathbf{a}_0 \exp\left(-\frac{r^2}{r_0^2} - \frac{\mathbf{x}^2}{(c\mathbf{t})^2}\right), \quad (4)$$

and the gas is neutral one at $\mathbf{x} = +\infty$ with $n_0(r, z, \mathbf{x} = +\infty) = n_{\text{at}}$. For such laser beam the Rayleigh length $z_R = \mathbf{w}_0 r_0^2 / 2c$.

Results.

Further we discuss such parameters which completely exclude the possibility of the sufficient wakefield generation in the preformed plasma. Namely the whole laser pulse form is a Gaussian one (in contrast to the flat top form in [10] with sharp leading edge) with $\mathbf{t}\Omega_p \gg 1$, where $\Omega_p^2 = (4\mathbf{p}e^2/m) \int_{-\infty}^{+\infty} \Gamma_0 dt$ and Γ_0 is taken on the laser beam axis $r = 0$, and laser pulse power P is small compare to the critical power for the relativistic self-focusing P_c . In particular there is no noticeable wakefield in the preformed plasma in Fig.1. Below the following dimensionless parameters are fixed: $P/P_c = 0.66 < 1$, $r_0\Omega_p/c = 23 \gg 1$, $a_0 = 0.2 \ll 1$, $\mathbf{t}\Omega_p = 50 \gg 1$. The gas is helium and the laser pulse wave length $\mathbf{I}_0 = 2\pi c/\mathbf{w}_0 = 0.8 \mu\text{m}$. With such parameters the laser pulse peak intensity I_0 appears to be fixed too: $I_0 = 8.55 \times 10^{16} \text{ W/cm}^2$. Thus if the value of one of the physical dimensional parameter is chosen (for example radius r_0) the values of others (n_{at} , P , \mathbf{t} , z_R) become fixed. Here in Fig.1-4 we present the results for three sets of such values:

$$\begin{aligned} \{r_0 = 29.3 \mu\text{m}, n_{\text{at}} = 8.7 \times 10^{18} \text{ cm}^{-3}, P = 1.1 \text{ TW}, \mathbf{t} = 212 \text{ fs}, z_R = 3.4 \text{ mm}, \mathbf{g} = 10, L_p = 0.4 \text{ mm}\}, \\ \{r_0 = 58.6 \mu\text{m}, n_{\text{at}} = 2.2 \times 10^{18} \text{ cm}^{-3}, P = 4.5 \text{ TW}, \mathbf{t} = 425 \text{ fs}, z_R = 13.5 \text{ mm}, \mathbf{g} = 20, L_p = 3.2 \text{ mm}\}, \\ \{r_0 = 146.4 \mu\text{m}, n_{\text{at}} = 0.35 \times 10^{18} \text{ cm}^{-3}, P = 28.1 \text{ TW}, \mathbf{t} = 1062 \text{ fs}, z_R = 84.2 \text{ mm}, \mathbf{g} = 50, L_p = 50 \text{ mm}\}, \end{aligned} \quad (5)$$

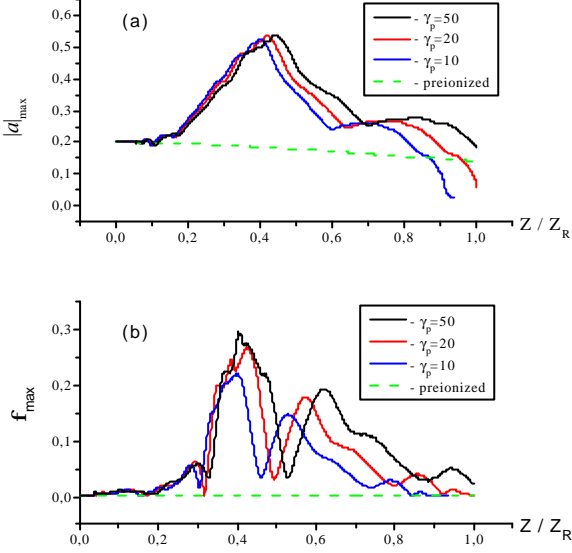
where $\mathbf{g} = \mathbf{w}_0/\Omega_p$ is the relativistic factor associated with group velocity, $L_p = (\mathbf{I}_p/2)(\mathbf{I}_p/\mathbf{I}_0)^2$ the dephase length, $\mathbf{I}_p = 2\pi c/\Omega_p$ the plasma wave length [3].

Fig.1 demonstrates the maximum wakefield potential amplitude \mathbf{f}_{max} as a function of the laser pulse penetration depth z (normalized on z_R) in helium. According to this figure the potential amplitude of the plasma wave generated after the neutral gas ionization is noticeable even at the near entrance of the gas. For comparison in preionized plasma an amplitude of the wakefield potential appears to be $\mathbf{f}_{\text{max}} \approx 10^{-136}$ [8]. The appearance of such noticeable plasma wave is stipulated by the ionization wakefield generation mechanism [1] which generates the wakefield at the entrance of the gas (see Fig.2). The magnitude of the plasma wave is higher compare to the predictions of the 1-D model [1] in the case of linear polarization of the laser pulse and is very close to that in the case of circular polarization. In contrast to the model [1] the magnitude of the above wakefield is very slightly dependent on the laser pulse polarization and is close to the circular polarization predictions. This circumstance originates from the strong difference in wakefield generation conditions here and in [1]. Namely here the laser pulse is comparatively long ($\mathbf{t}\Omega_p = 50 \gg 1$) and the ionization front duration is of the order of the period of the generated plasma wave. In model [1] the width of the ionization front is implied to be zero. In addition Fig.2 demonstrates that the contribution of different integral ionization terms in system (1) into the wakefield amplitude is near negligible.

The nature of the wakefield seed for the self-modulation amplification changes as the pulse penetrates into the gas. Namely the strong ionization refraction at the very leading edge of the pulse drastically deformats the laser pulse temporal profile with strong steepening. The laser pulse form becomes so sharp that about 75 % of the plasma wave seed for the self-modulation amplification is provided by the mechanism of [8]. Besides Fig.1 demonstrates the absence of the wakefield in the conditions of Fig.1 along the whole passage in the preliminary created plasma. Spatial behavior of the wakefield at different values of \mathbf{g} are very similar to each other. The reasonable value of the plasma wave potential \mathbf{f}_{max} spreads over different distances L at above different sets of parameters. As a result the electron energy gain from plasma wave electric field $\Delta W_e \approx |e|E_{p,z,\text{max}}L \approx \mathbf{f}_{\text{max}}L\Omega_p/c \times mc^2$ is different for different values of \mathbf{g} :

$$\Delta W_e = 40 \text{ MeV at } \mathbf{g} = 10, \quad \Delta W_e = 90 \text{ MeV at } \mathbf{g} = 20, \quad \Delta W_e = 400 \text{ MeV at } \mathbf{g} = 50.$$

Helium: $I_0=8.55*10^{16} \text{W/cm}^2$, $\lambda_0=0.8\mu\text{m}$, $k_p r_0=23$, $k_p L=50$
 $\xi=10$: $n_{\text{at}}=8.7*10^{18} \text{cm}^{-3}$, $t=212\text{fs}$, $r_0=29\text{mm}$, $Z_R=0.34\text{cm}$, $P=1.1\text{TW}$
 $\xi=20$: $n_{\text{at}}=2.2*10^{18} \text{cm}^{-3}$, $t=425\text{fs}$, $r_0=59\text{mm}$, $Z_R=1.35\text{cm}$, $P=4.5\text{TW}$
 $\xi=50$: $n_{\text{at}}=0.35*10^{18} \text{cm}^{-3}$, $t=1.1\text{ps}$, $r_0=146\text{mm}$, $Z_R=8.4\text{cm}$, $P=28\text{TW}$



$\xi=10$: dephasing length $L = 0.4\text{mm} = 0.12 Z_R$, $DW_e = 40\text{MeV}$
 $\xi=20$: dephasing length $L = 3.2\text{mm} = 0.24 Z_R$, $DW_e = 90\text{MeV}$
 $\xi=50$: dephasing length $L = 50 \text{ mm} = 0.6 Z_R$, $DW_e = 400\text{MeV}$

Fig.1 Maximum normalized laser electric field $|E|$ (a) and f_{max} (b) as functions of the normalized laser pulse penetration depth z/z_R . The gas is helium and laser-gas parameters correspond to three sets of parameters (see (5)).

Fig.3 shows the contour plots of the laser pulse electric field a , wakefield potential f on the plane $(rk_p, \mathbf{x}k_p)$ and the enlarged drawing of the wakefield potential f in the vicinity of $\mathbf{x} = 0$, $r = 0$ at the position $z = 0.4 \times z_R$. The laser-gas parameters are of the first set of (5).

Fig.4 shows the contour plots of the electron density n_e normalized on Zn_{at} at different penetration depths z : $z = 0.2 \times z_R$, $z = 0.4 \times z_R$, $z = 0.6 \times z_R$. The laser-gas parameters are the same as in Fig.3.

Conclusions.

The above results demonstrate that the intensive laser pulse propagating in the gas being ionized is an effective generator of the plasma wakefield with reasonable parameters for electron acceleration. To increase the energy gain it makes sense to decrease the background gas density. Being under critical power for relativistic self-focusing with the laser parameters $I_0 = 0.8 \mu\text{m}$, $r_0 = 146.4 \mu\text{m}$, $P = 28.1 \text{ TW}$, $t = 1.1 \text{ ps}$ and helium density $n_{\text{at}} = 0.35 \times 10^{18} \text{ cm}^{-3}$ we gets the electron energy gain $\Delta W_e = 400 \text{ MeV}$ on a distance about 5 cm ($0.6 \times z_R$).

Above results are not in contradiction with experimental observations [5]. Namely experiments [5] with low power laser beam are carried out at such laser-plasma conditions when the value of the plasma wave length $\lambda_p = 2\pi c/\Omega_p$ is close to the laser beam radius r_0 . Above regular wakefield structures and corresponding acceleration are obtained at $\lambda_p \ll r_0$. If the laser beam radius is decreased down to the plasma wave length in

Ionization seed of self-modulation at $z = 0$

Helium: $I_0=8.55*10^{16} \text{W/cm}^2$, $\lambda_0=0.8\mu\text{m}$, $k_p r_0=23$, $\Omega_p \tau = 50$
 $\xi=10$: $n_{\text{at}}=8.7*10^{18} \text{cm}^{-3}$, $t=212 \text{ fs}$, $r_0=29\mu\text{m}$, $Z_R=0.34\text{cm}$, $P = 1.1\text{TW}$

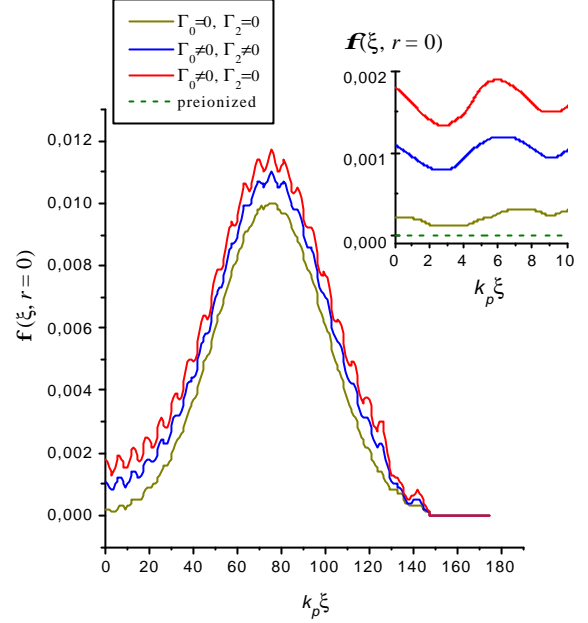


Fig.2 f as a function of $\mathbf{x} \times k_p$ at $z = 0$ as a solution of (1)-(4) when different integral terms (proportional to Γ_0 and Γ_2) in (1) are taken into account. Three possibilities are presented: ($\Gamma_0 \neq 0$, $\Gamma_2 \neq 0$) corresponds to the linearly polarized pulse, ($\Gamma_0 \neq 0$, $\Gamma_2 = 0$) corresponds to the circular polarization, ($\Gamma_0 = 0$, $\Gamma_2 = 0$) corresponds to the absence of the integral terms in (1). The enlarged region which corresponds to the laser pulse tail is shown. The curve corresponding to the preionized plasma is added. Laser-gas parameters correspond to the first set of (5).

Helium: $I_0 = 8.55 \cdot 10^{16}$ W/cm², $\lambda_0 = 0.8$ μ m, $k_p r_0 = 23$, $\Omega_p \tau = 50$

$g_g = 10$: $n_{at} = 8.7 \cdot 10^{18}$ cm⁻³, $t = 212$ fs, $r_0 = 29$ μ m, $z_R = 0.34$ cm, $P = 1.1$ TW

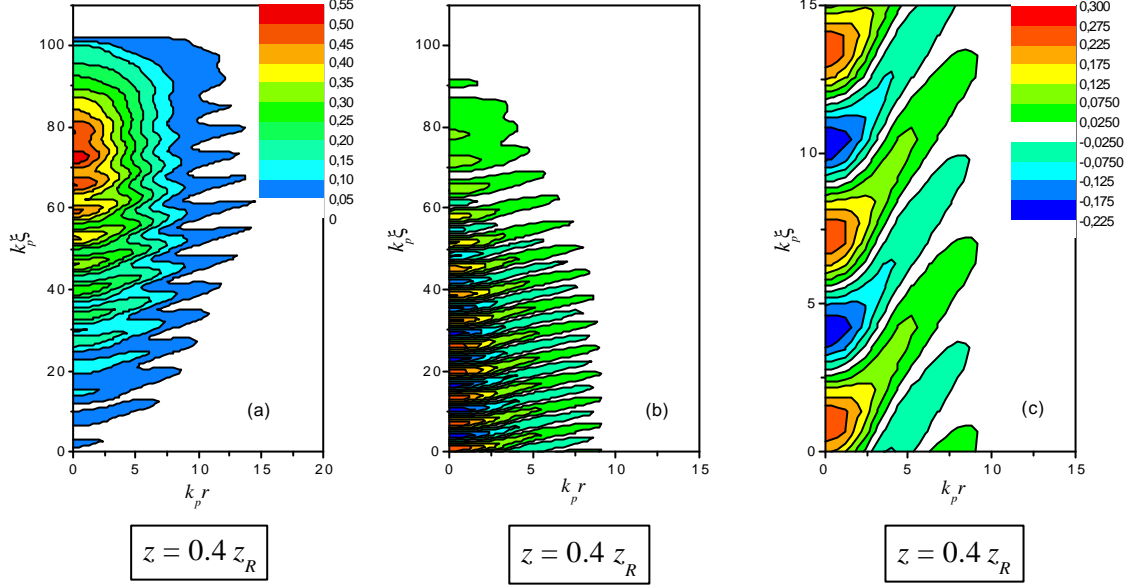


Fig.3 The contour plots of the normalized vector potential $|a|$ (a), wakefield potential F (b) on the plane $(rk_p, \mathbf{x}k_p)$ and the enlarged drawing of the wakefield potential F in the vicinity of $\mathbf{x} = 0$, $r = 0$ (c) at the position $z = 0.4 \times z_R$. The initial laser peak intensity position is determined by $\mathbf{x}k_p = 75$. The laser pulse and gas parameters are from the first set of (5).

Helium: $I_0 = 8.55 \cdot 10^{16}$ W/cm², $\lambda_0 = 0.8$ μ m, $k_p r_0 = 23$, $\Omega_p \tau = 50$

$g_g = 10$: $n_{at} = 8.7 \cdot 10^{18}$ cm⁻³, $t = 212$ fs, $r_0 = 29$ μ m, $z_R = 0.34$ cm, $P = 1.1$ TW

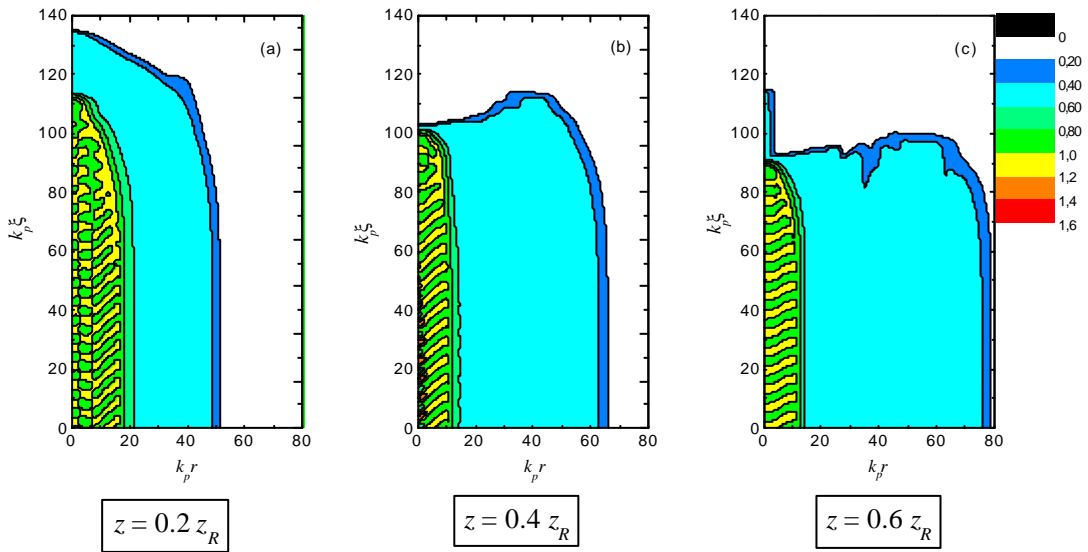


Fig.4 The contour plots of the electron density n_e normalized on Zn_{at} on the plane $(rk_p, \mathbf{x}k_p)$ at different penetration depths z : $z = 0.2 \times z_R$ (a), $z = 0.4 \times z_R$ (b), $z = 0.6 \times z_R$ (c). The laser-gas parameters are the same as in Fig.3.

our calculations self-modulation can not develop in such narrow ionization plasma column. As a result an amplitude of the plasma wakefield remains at the same small level as the seed at the ionization front.

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