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Two-fluid computations of plasma block dynamics for numerical analyze of rippling effect

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Abstract

In this paper the results of numerical computations of rippling smoothing basing on the broad-band laser irradiation method for the laser intensity range $10^{16}-10^{17}$ W/cm^2 and short-pulse ($<$10 ps) interaction with plasma are described.

Keywords: Density rippling; Genuine two-fluid computations; Laser-plasma interaction; Nonlinear (ponderomotive) force; Plasma blocks; Smoothing by broad-band laser smoothing

1. INTRODUCTION

In order to use a high-energy and short-pulse laser-plasma interaction for direct-drive laser fusion, we are obliged to reduce a number of setbacks received from the experimental observation. Such a problem was caused by non-linear and anomalous phenomena and was mentioned in the 1960s and 1970s.

The major obstacles to achieving a direct-drive fusion are Rayleigh–Taylor instability and stochastic pulsation. For the last year, a lot of efforts were made by many research groups all over the world in order to reduce the second effect. For example, in the paper of Boreham *et al.* (1997), basing on genuine two-fluid model, it investigated interaction between three wave-set with plasma, leading to reduction of rippling amplitude for long pulses with $\tau_L > 20$ ps and for beam intensity in the range 10^{15} W/cm^2 to 10^{16} W/cm^2.

The stochastic pulsation was recognized from numerical studies in 1974 at the University of Rochester (Hora, 1991: Figs. 10.10 and 10.11; Hoffmann *et al.*, 1990) and measured most convincingly by Maddever *et al.* (1990). The theory (Hora & Aydin, 1992) confirmed this mechanism and how this could be overcome by laser beam smoothing, especially by broad band irradiation (Hora & Aydin, 1999; Osman & Hora, 2004). The following approach is specifically directed to analyze new developments of the plasma block generation (Hora *et al.*, 2002; Badziak *et al.*, 2004*a*, 2004*b*) as an alternative scheme for laser fusion (Hora, 2004) as one option of fast ignition (Bauer, 2003; Deutsch, 2004; Mulser & Schneider, 2004; Mulser & Bauer, 2004; Osman & Hora, 2004; Ramirez *et al.*, 2004; Hoffmann *et al.*, 2005; Badziak *et al.*, 2005).

Due to fast progress in laser technology, there are in use now laser systems generating pico and sub-pico second pulses with intensities above 10^{16} W/cm^2. In this paper the results of numerical computations of rippling smoothing for the laser intensity range 10^{16}–10^{18} W/cm^2 and short-pulse ($<$10 ps) interaction with plasma are described.

2. THE WAYS OF REDUCTION OF STOCHASTIC PULSATION

The mechanism of stochastic pulsation was first explained in 1974 when the mentioned phenomena were bound with interaction between laser field and plasma. Due to a big value of ponderomotive force, it is possible to observe rippling of electrons and ions density profiles. Such a self-generated von-Laue grating prevents the propagation of laser radiation through the plasma and prevents energy deposition to the critical region of plasma. Due to a thermal relaxation, gratings disappear after some time and all the phenomenon can repeat again if the interaction time is sufficiently long.

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In order to interrupt this pulsation for long laser pulses smoothing methods are usually used. The most popular of them are:

- **Random phase plate (RPP)** (Kato *et al.*, 1984)—generation of beamlets with random phase shift. Standing wave pattern generated by one beamlet is washed out by the neighboring beamlet,
- **Induced special incoherence (ISI)** (Lehmberg & Obenschain, 1983)—if the coherence of laser beam is correlated with the period of arising of standing wave no density ripple can be produced,
- **Broad-band laser irradiation** (Deng *et al.*, 1986*a*, 1986*b*)—when some waves with different frequency simultaneously pass through plasma rippling is suppressed.

In this paper, the last method of smoothing is investigated. Broad-band irradiation was simulated by analyzing the interaction between three or five wave-sets with plasma. The difference between frequencies of waves in wave-set was in the range 0.5–2.0% of ω_0.

3. TWO-FLUID HYDRODYNAMIC MODEL

The interaction of a short laser pulse with an inhomogeneous plasma layer was investigated by Glowacz *et al.* (2004) with the use of the computation code of the advanced two-fluid plasma model. This model is based on the nontermalized direct electromagnetic interaction between the laser light and the fully ionized plasma. In this model, electrons and ions are treated as separate conductive fluids which interact between each other by collisions (momentum exchange) and the Coulomb interaction. The electron and ion fluids are described by six quantities which are mass densities (ρ_e, ρ_i), temperatures (T_e, T_i), and velocities of electrons and ions (v_e, v_i). The equations of the model were solved in one dimension which means that all just mentioned quantities depend on one spatial coordinate (x) and time (t). The velocities v_e and v_i are in the x-direction.

To obtain these six quantities we solved six equations and particularly: the equations of continuity for electrons and ions

$$\frac{\partial}{\partial t}\rho_e = -\frac{\partial}{\partial x}(\rho_e v_e), \tag{1}$$

$$\frac{\partial}{\partial t}\rho_i = -\frac{\partial}{\partial x}(\rho_i v_i), \tag{2}$$

the equations describing conservation of momentum for electrons and ions

$$\frac{\partial}{\partial t}(\rho_e v_e) = -\frac{\partial}{\partial x}(\rho_e v_e^2) - \frac{\partial}{\partial x}p_e - \frac{e}{4\pi}\frac{\partial E_x}{\partial x} - \rho_e \nu (v_e - v_i) + f_{nl}, \tag{3}$$

$$\frac{\partial}{\partial t}(\rho_i v_i) = -\frac{\partial}{\partial x}(\rho_i v_i^2) - \frac{\partial}{\partial x}p_i - \frac{e}{4\pi}\frac{\partial E_x}{\partial x} + \rho_e \nu (v_e - v_i) + \frac{m_e}{m_i} f_{nl}, \tag{4}$$

and the equations which allow us to take into account changes of the temperature of ions and electrons (conservation of energy)

$$\frac{\partial}{\partial t}(\rho_e \varepsilon_e) = -\frac{\partial}{\partial x}(\rho_e \varepsilon_e v_e) - p_e\frac{\partial v_e}{\partial x} - \frac{3}{2}\frac{k_B n_e}{\tau}(T_e - T_i) + \frac{\partial}{\partial x}\left(\kappa_e \frac{\partial T_e}{\partial x}\right) + W_L, \tag{5}$$

$$\frac{\partial}{\partial t}(\rho_i \varepsilon_i) = -\frac{\partial}{\partial x}(\rho_i \varepsilon_i v_i) - p_i\frac{\partial v_i}{\partial x} + \frac{3}{2}\frac{k_B n_e}{\tau}(T_e - T_i) + \frac{\partial}{\partial x}\left(\kappa_i \frac{\partial T_i}{\partial x}\right). \tag{6}$$

It was assumed that equations of state for these two fluids are $p_e = k_B T_e \rho_e / m_e$, $p_i = k_B T_i \rho_i / m_i$ (ideal gas), where k_B is the Boltzman constant and electron and ion mass are m_e and m_i, respectively. As ε_e is internal energy of electrons and ε_i is energy of ions, we can replace these quantities with temperatures using $\varepsilon_e = 3/2 k_B T_e / m_e$ for electrons, and $\varepsilon_I = 3/2 k_B T_i / m_i$ for ions. The quantities ν, t, and W_L are the collision frequency, the temperature equipartition time, and the density of electron heating power by laser absorption in plasma. The formulas for κ_e and κ_i which are thermal conductivities for the electron and ion fluids, respectively, must be known.

To describe the Coulomb interaction between the two charged fluids, which play the most crucial role in the ion current appearance, Poisson equation was solved

$$\frac{\partial E_x}{\partial t} = 4\pi e(n_i v_i - n_e v_e), \tag{7}$$

where E_x is the electric field in the x-direction, *ni* and *ne* are the electron and ion number densities, respectively.

To find non-linear ponderomotive force ($\mathbf{f}_{NL} = 1/c\mathbf{j} \times \mathbf{H}$) in the x-direction ($\mathbf{f}_{NL}$) and the density of electron heating power (W_L), the electromagnetic wave equations in plasma were solved

$$\frac{\partial^2}{\partial x^2}E_z = \frac{1}{c^2}\frac{\partial}{\partial t^2}E_z + \frac{4\pi}{c^2}\frac{\partial}{\partial t}j_z \tag{8}$$

$$\frac{\partial}{\partial t}j_z = \frac{\omega_p^2}{4\pi}\left(E_z + \frac{1}{c}v_e H_y\right) - \nu j_z \tag{9}$$

$$\frac{\partial}{\partial t}H_y = c\frac{\partial}{\partial x}E_z, \tag{10}$$

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where E_z and H_y, are electric and magnetic fields of laser light and jz is a current in the z-direction. The impact of electron motion in electric field of light wave on the collision frequency ν, was taken into account. The equations of the model were solved basing on the Lax method.

4. NUMERICAL TOOL FOR ESTIMATING OF THE RIPPLING EFFECT

In order to estimate level of rippling effect and results of smoothing an especial numerical tool based on the multilayers stack theory was created.

The main idea of the method is simple:

- the region of plasma is divided into many layers of Δx width (Δx is equal space step used in main simulating program);
- within each layer refractive index is constant and is dependent on collision frequency ν, plasma frequency ω_p, and laser pulse frequency ω;
- the laser pulse propagating through such a stack is reflected and the level of reflection can be used as an indicator of rippling.

For the derivation of main equations for multilayers method phase relationship between electric E, and magnetic H fields on the layer's border was taken into consideration (Fig. 1).

The values for E and H evaluated on the first border were used for evaluating such values on the next border and so on.

The main relations used in the method are described below:

$$\begin{bmatrix} \tilde{E}_0^i \\ \tilde{E}_0^r \end{bmatrix} = \frac{1}{2} \begin{bmatrix} \left(\frac{\tilde{n}_1}{\tilde{n}_0}+1\right) e^{-jk_0 \tilde{n}_1 \Delta x} & -\left(\frac{\tilde{n}_1}{\tilde{n}_0}-1\right) e^{jk_0 \tilde{n}_1 \Delta x} \\ -\left(\frac{\tilde{n}_1}{\tilde{n}_0}-1\right) e^{-jk_0 \tilde{n}_1 \Delta x} & \left(\frac{\tilde{n}_1}{\tilde{n}_0}+1\right) e^{jk_0 \tilde{n}_1 \Delta x} \end{bmatrix} \times \begin{bmatrix} \tilde{E}_1^i \\ \tilde{E}_1^r \end{bmatrix}, \tag{11}$$

$$\begin{bmatrix} \tilde{E}_0^i \\ \tilde{E}_0^r \end{bmatrix} = M_1 M_2 \cdots M_{N-1} M_N \begin{bmatrix} \tilde{E}_N^i \\ \tilde{E}_N^r \end{bmatrix}, \tag{12}$$

$$R = \left(\frac{\tilde{E}_0^r}{\tilde{E}_0^i}\right)^2 - \textit{coefficient of reflectivity}, \tag{13}$$

$$\tilde{n}_n = \sqrt{1 - \frac{\omega_p^2(n)}{\omega^2\left(1 - i\,\frac{\nu(n)}{\omega}\right)}}, \tag{14}$$

where

$\tilde{E}_n^i, \tilde{E}_n^r$ = complex amplitude of electric fields for incident and reflected waves in layer number n,

$\tilde{n}_n$ = complex refractive index,

M_n = complex matrix connecting amplitude of electric fields between layers n and $n-1$,

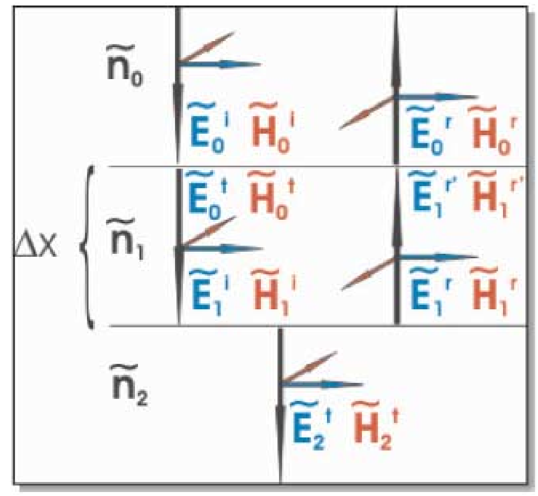

Fig. 1. The idea of multilayers method of rippling evaluation.

ω_p, ω, ν = plasma frequency, wave frequency and electron ion collision frequency.

The example of correlation between plasma profile and refractive coefficient is shown in Figure 2. Analyzing the data in Figure 2, we can see that for plasma block width of 2.5 μm reflectivity coefficient is equal to about 18%, but for the width of 5 μm this value reach 62%. For ion density profile without rippling, reflectivity coefficients are equal about 0% for the width of 2.5 μm and 5 μm (Fig. 3).

A characteristic 100% reflection for plasma 13.5 μm wide is a result of reflection from critical density region n_{cr}.

5. RESULTS AND DISCUSSION

The numerical calculations were performed for 20 μm hydrogen, inhomogeneous plasma layer of initial density increasing in the direction of the laser beam propagation.

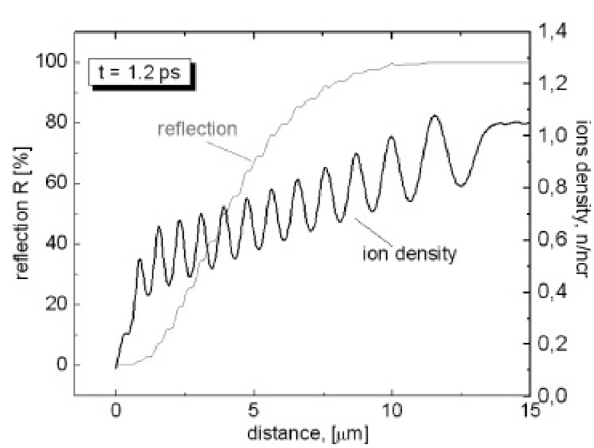

Fig. 2. Reflection of laser beam from plasma region as a function of the distance and ion density profile. $T = 1.2$ ps, $I = 10^{16}$ W/cm^2, $\tau_{1/2} = 1$ ps, $\lambda = 1.06$ μm.

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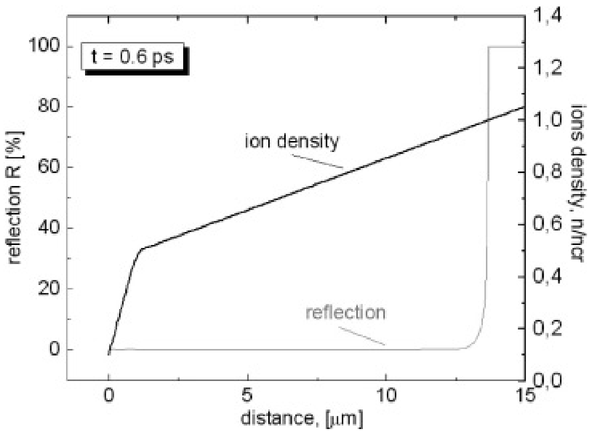

Fig. 3. Reflection of laser beam from plasma region as a function of the distance and ion density profile for time $t = 0.6$ ps since start of interaction. $I = 10^{16}$ W/cm^2, $\tau_{1/2} = 1$ ps, $\lambda = 1.06$ μm.

Linear plasma density profile described by the function $n(x) = (0.04x + 0.5)n_{cr}$, where n_{cr}—critical density, x—distance from plasma face in μm was taken into consideration. The mentioned density profile was preceded by short 1 μm plasma layer with a steeper density profile in order to improve numerical stability (Fig. 3). The computations were made for two laser intensities 10^{16} W/cm^2 and 10^{17} W/cm^2. For each intensity one wave, three waves, and five waves cases of interaction with plasma were analyzed (Table 1). In the case of multi waves, the total maximum amplitude of electric E and magnetic H components for waves was equal to the maximum amplitude E and H for one wave case. The parameter "relative intensity of laser beam" describes the relation between total intensity (not maximum intensity) of the laser pulse used during computations, relatively to the total intensity of one wave case. It should be noticed that this relation is constant and independent of shift $\Delta\omega$, see Figure 4. The decrease in the total intensity in the function of the wave's quantity is a result of interference between multi wave's elements in laser pulse. Results for intensity 10^{16} W/cm^2 are presented in Figure 5 to Figure 8.

Basing on the figures presented above we observed that for maximum of laser pulse intensity 10^{16} W/cm^2, differences between interaction with plasma for one wave and multi-waves beams gives, for maximum ion velocity, very similar results in both directions of the plasma block propagation. Such an effect may be a surprise when we remember the fact that total intensity of the pulse in the cases of three and five waves is much smaller than in the case of one wave Figure 4. The main reason for the observed phenomena is only one, the smoothing of rippling effect. The most reduction of rippling amplitude was observed for frequency shift $\Delta\omega = 0.5\%$ ω_0 (three waves) and for $\Delta\omega = 1.0\%$ ω_0 (five waves). The mentioned amplitudes were decreased 3 times and 5 times, respectively. This fact was theoretically proved by Glowacz *et al*. (2006).

Similar relations were observed for higher pulse intensity $I = 10^{17}$ W/cm^2, Figure 9 to Figure 12, but for this example, an advantageous influence of smoothing was much more distinct and maximum values of ion velocities were about 2.5–3.0 times greater than for the case without smoothing.

It must be necessarily said that the method analyzed in the paper, which is well known for longer pulses can be successfully used to improve of the interaction between short ($<$1 ps) laser pulses and plasma.

6. CONCLUSIONS

- Using of broad-band laser irradiation method for rippling smoothing always lead to decreasing of the plasma reflection, particularly for early times of laser beam-plasma interaction.
- The lower average power density for three waves and five waves methods of smoothing in relation to one wave case (33% for 3 waves, 20% for 5 waves) does not cause of decreasing of ion velocity (this fact confirm negative role of rippling for energy exchanging between laser beam and plasma).
- For both intensities of laser beam, took into consideration (10^{16} W/cm^2 and 10^{17} W/cm^2) optimal values of frequency shift for three waves and five waves methods are established. For three waves smoothing optimal value is for $\Delta\omega \approx 0.5\%$, but for five waves such value is for $\Delta\omega \approx 1.0\%$.
- For the case of optimal smoothing, amplitude of rippling is suppressed about 3 times, relatively to the case without smoothing.

Table 1. *Parameters of laser beams used during computations*

Parameter	one wave	three waves	five waves
Length of laser pulse [ps]	1.0	1.0	1.0
Length of wave [μm]	1.06	1.06	1.06
Frequency of wave ω_0 [Hz]	1.785 10^{15}	1.785 10^{15}	1.785 10^{15}
Frequency structure of pulse	ω_0	$\omega_0 - \Delta\omega, \omega_0, \omega_0 + \Delta\omega$	$\omega_0 - 2\Delta\omega, \omega_0 - \Delta\omega, \omega_0, \omega_0 + \Delta\omega, \omega_0 + 2\Delta\omega$
Analysed shifts $\Delta\omega$ [% of ω_0]	0.0	0.5, 1.0, 1.5, 2.0	0.5, 1.0, 1.5, 2.0
Max. intensity of laser beam [W/cm^2]	10^{16}, 10^{17}	10^{16}, 10^{17}	10^{16}, 10^{17}
Relative intensity of laser beam	1.000 I_0	0.333 I_0	0.200 I_0

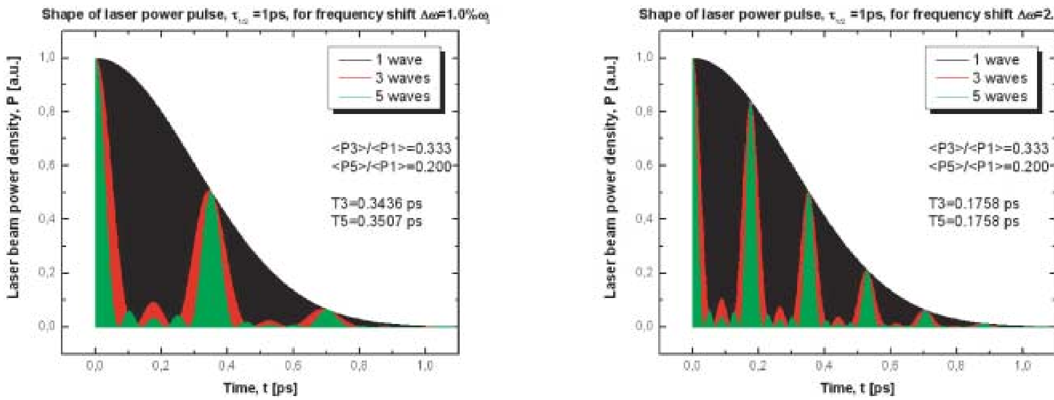

Fig. 4. Shapes of the laser pulse intensity for frequency shift between waves: 1.0% of ω_0 (left figure) and 2% of ω_0 (right figure).

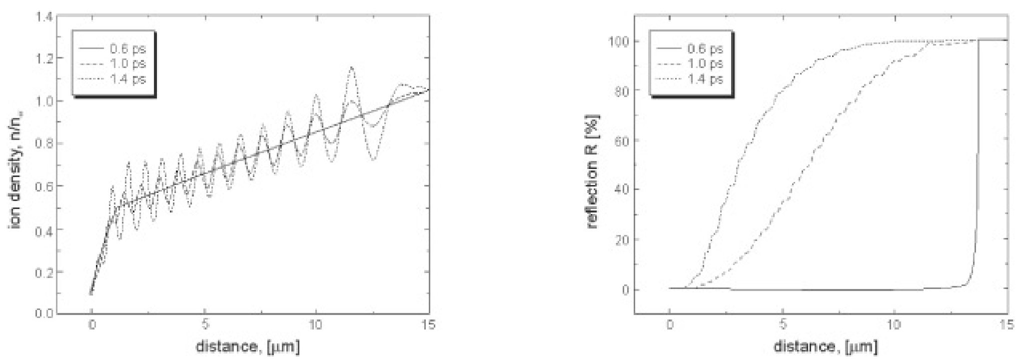

Fig. 5. Evolution of ion density profile (left figure) and reflection of laser beam from plasma region (right figure) as a function of distance and interaction time for one wave. $I = 10^{16}$ W/cm^2, $\tau_L = 1$ ps, $\lambda = 1.06$ μm.

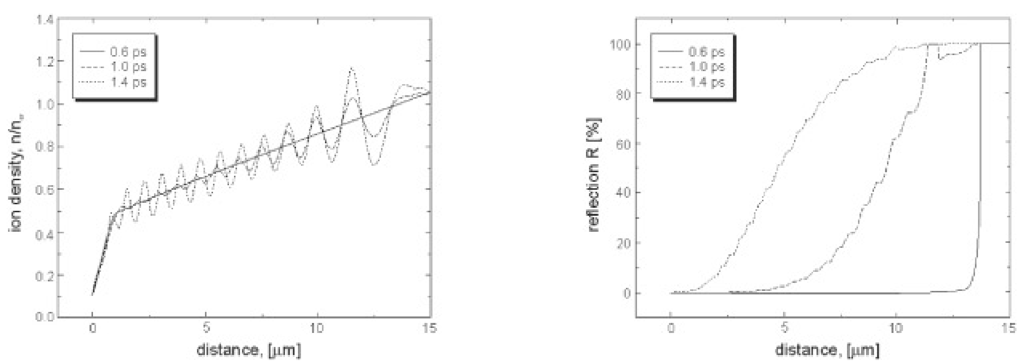

Fig. 6. Evolution of ion density profile (left figure) and reflection of laser beam from plasma region (right figure) as a function of distance and interaction time for three waves of $\Delta\omega = 0.5\%$ ω_0. $I = 10^{16}$ W/cm^2, $\tau_L = 1$ ps, $\lambda = 1.06$ μm.

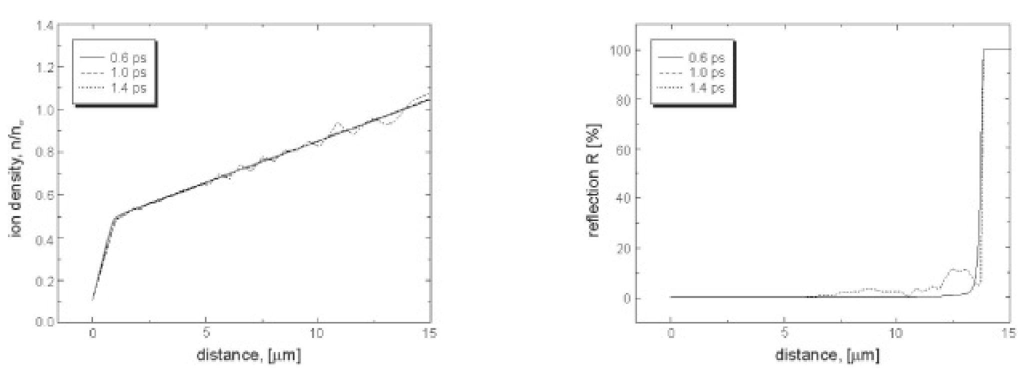

Fig. 7. Evolution of ion density profile (left figure) and reflection of laser beam from plasma region (right figure) as a function of distance and interaction time for five waves of $\Delta\omega = 1.0\%$ ω_0. $I = 10^{16}$ W/cm^2, $\tau_L = 1$ ps, $\lambda = 1.06$ μm.

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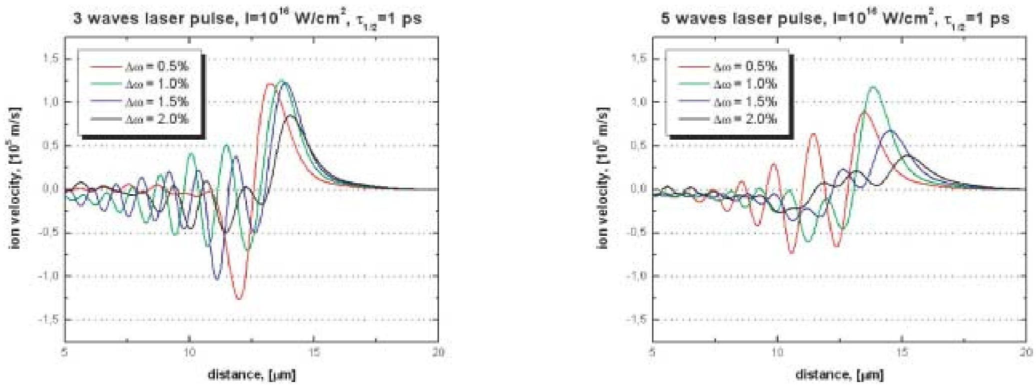

Fig. 8. Evolution of the ion velocity profile for three waves (left figure) and for five waves (right figure), results for 2 ps after the start of interaction. $I = 10^{16}$ W/cm^2, $\tau_L = 1$ ps, $\lambda = 1.06$ μm.

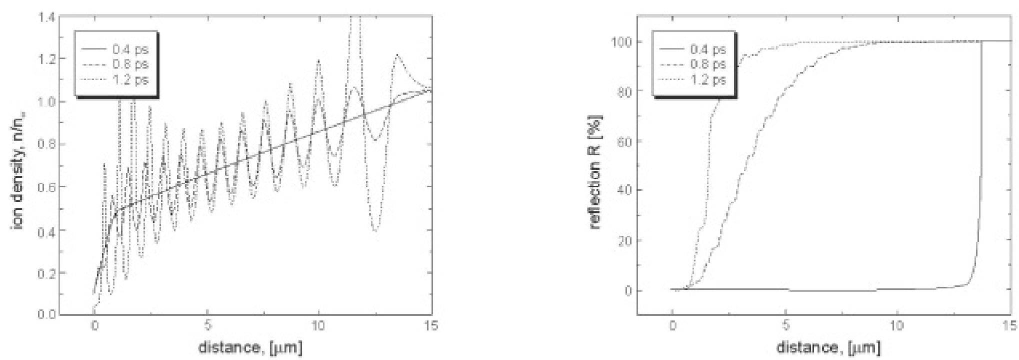

Fig. 9. Evolution of ion density profile (left figure) and reflection of laser beam from plasma region (right figure) as a function of distance and interaction time for one wave. $I = 10^{17}$ W/cm^2, $\tau_L = 1$ ps, $\lambda = 1.06$ μm.

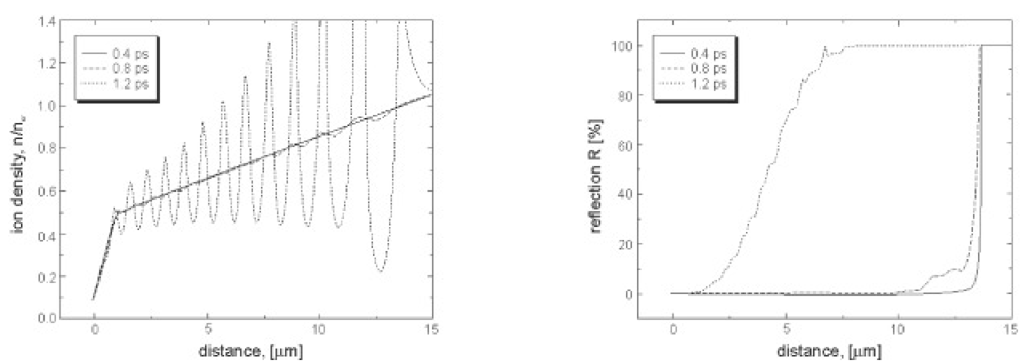

Fig. 10. Evolution of ion density profile (left figure) and reflection of laser beam from plasma region (right figure) as a function of distance and interaction time for three waves of $\Delta\omega = 0.5\%\ \omega_0$. $I = 10^{17}$ W/cm^2, $\tau_L = 1$ ps, $\lambda = 1.06$ μm.

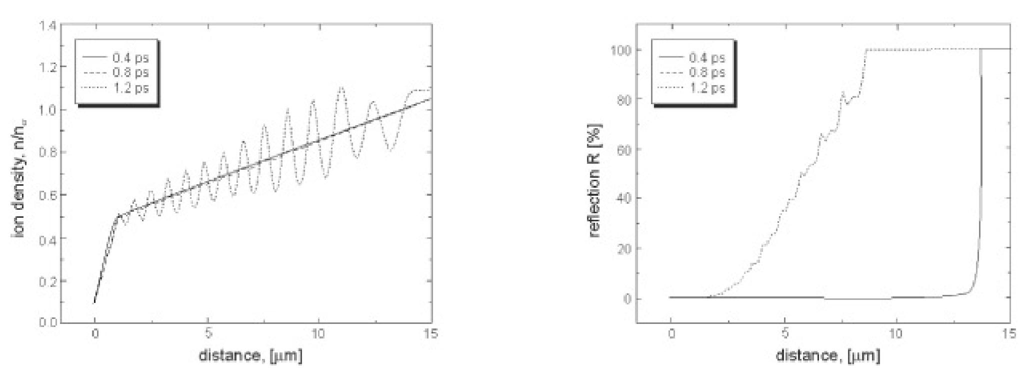

Fig. 11. Evolution of ion density profile (left figure) and reflection of laser beam from plasma region (right figure) as a function of distance and interaction time for five waves of $\Delta\omega = 1.0\%\ \omega_0$. $I = 10^{17}$ W/cm^2, $\tau_L = 1$ ps, $\lambda = 1.06$ μm.

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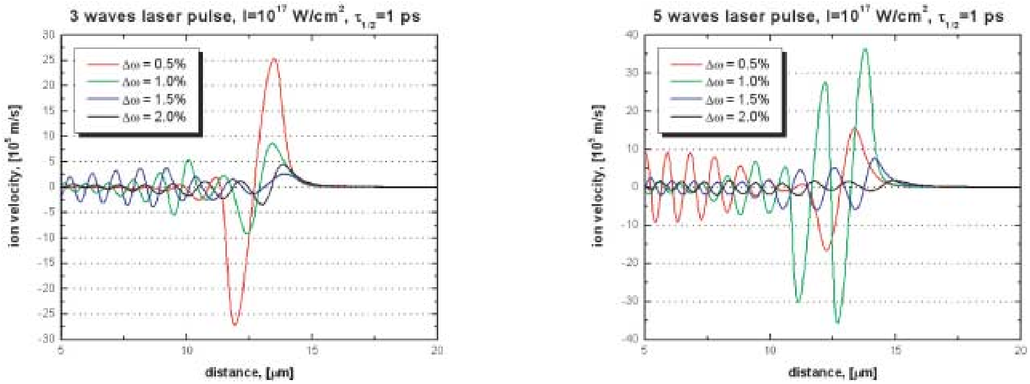

Fig. 12. Evolution of the ion velocity profile for three waves (left figure) and for five waves (right figure), results for 1.5 ps after the start of interaction. $I = 10^{17}$ W/cm^2, $\tau_L = 1$ ps, $\lambda = 1.06\ \mu$m

- Mentioned above broad-band method is a good tool for smoothing of rippling for short pulse (1 ps) and high-energy laser-beam interaction with plasma.

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