3D PIC modeling of laser acceleration of electrons from two-dimensional inhomogeneous plasma corona

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Abstract. This paper presents the results of three-dimensional (3D3V) particle-in-cell modeling of the interaction of a femtosecond laser pulse with a two-dimensional inhomogeneous plasma corona of subcritical density. It was shown that in the presence of sufficiently steep temporal pulse edge the excitation of plasma waves, electron trapping and generation of collimated beams of accelerated electrons with energy of about 0.2–0.5 MeV may occur. The simulation results are compared with experiments on the generation of collimated beams of accelerated electrons from metal targets irradiated by intense femtosecond laser radiation.

1. Introduction

A plasma wake wave created by an intense subpicosecond laser pulse may be used for efficient acceleration of electrons [1,2]. The longitudinal electric field in such a wave can be several orders of magnitude higher than that achievable in standard high-frequency accelerators. This feature allows to create compact particle accelerators for various applications.

To obtain reproducible quasimonoenergetic electron beams with a given energy required for applications the process of external injection in a weakly nonlinear wakefield can be used in which particles are accelerated in a regular plasma wave without wave breaking [2]. In contrast to the cavitation regime [3], because of the relatively low plasma wakefield amplitude in this regime the electron energy threshold for trapping is much higher and the problem of electron injection into the plasma wave is highly relevant. The excitation of a weakly nonlinear plasma wake waves over large lengths needed to accelerate electrons to energies of hundreds of MeV has already been demonstrated for the geometry of the dielectric capillary [4,5]. However, the method of the synchronized with the laser pulse electron injection into the wave has not been developed. To date, various schemes of laser-plasma acceleration have been demonstrated in which the injection and acceleration of electrons can be controlled independently to obtain more stable beams with a specified energy [6–8].

In this paper, we apply the three-dimensional (3D3V) PIC simulations analysis with the code VLPL [9] to study the electron acceleration from one-dimensional and two-dimensional inhomogeneous plasma corona of subcritical density produced by focusing the laser prepulse radiation perpendicular to the plane of aluminum foil on its edge [10]. The results are compared with experiment, which revealed the generation of quasi-monoenergetic collimated electron beams with the energy at the maximum of the energy distribution in range 0.2–0.8 MeV [10,11].

2. Theoretical Description and Results

Parameters of the laser pulse incident on the plasma in simulations correspond to conditions of the experiment [10]. The laser pulse with a duration $\tau_L \cong 47$ fs at the intensity level of $\exp(-1)$ propagating along the OX axis has a transverse linear polarization along the OY axis and a Gaussian shape in the transverse direction with the width at half amplitude of intensity $d_{\mathrm{FWHM}} = 29.4$ μm. The wavelength of the laser pulse is $\lambda = 1$ μm, the dimensionless amplitude $a_L = eE_L/mc\omega = 0.468$, which corresponds to the intensity $I_L = 3 \times 10^{17}$ W/cm^2. Here e is the absolute value of the elementary charge, E_L is the amplitude of the laser electric field, m is the mass of the electron, c is the speed of light and ω is the laser frequency. The size of the simulation box is $(x, y, z) \in [0,\ 220;\ -75,\ 75;\ -75,\ 75]$ μm. At the initial moment the center of the laser pulse is at $(x_0,\ y_0,\ z_0) = (-20, 0, 0)$ μm. In the first series of simulations the plasma density profile $n(x)$ in the direction of the OX axis is inhomogeneous with the semi-Gaussian density variations at the plasma boundary with the characteristic size of inhomogeneity (exponential half-width) $l_x = 15$ μm and $l_x = 1$ μm used in 1D3V calculations in the previous work [10]. In the area of $0 \leq x \leq 40$ μm the density increases $(n(x) = \exp((x-40)^2/l_x^2))$, at $140 \leq x \leq 180$ μm it decreases $(n(x) = \exp((x-140)^2/l_x^2))$, and in the area $40 \leq x \leq 140$ μm the initial electron density of plasma

$$n(x,\ y,\ z) = n_e n(x) n(y) \tag{1}$$

is homogeneous ($n(x)$=1) and is equal to $n_e = 0.045 n_{cr} = 5 \times 10^{19}$ cm^{-3} at the axis of the laser pulse ($y = z = 0$), where $n_{cr} = m\omega^2/(4\pi e^2)$. Ions in the simulation are fixed and form a neutralizing background. Initially the plasma is considered to be cold. Cell sizes $\Delta x = 0.05$ μm, $\Delta y = \Delta z = 0.5$ μm and the number of particles per cell is 4.

To verify the findings of [10] about the possibility of electrons acceleration in the wake plasma waves excited in the laser-pulse self-modulation regime, first three-dimensional (3D3V) calculations were carried out with the homogeneous along the axes OY and OZ initial plasma density ($n(y) = 1$ in the expression (1)). This formulation is similar to the inhomogeneous one-dimensional approximation used earlier in the model (1D3V) calculations [10]. Three-dimensional (3D3V) simulations performed with the Gaussian temporal profile of the laser pulse, as well as in the one-dimensional case [10] show that for the smooth envelope and a relatively low intensity (3×10^{17} W/cm^2) of the pulse, a seed amplitude of the plasma wave is not sufficient for the development of self-modulation instability [12] and generation of accelerating wakefield. Calculations with the rectangular or hyper-Gaussian temporal envelope ($E_y \propto \exp\left[-(x/c\tau_L)^{2n}\right]$, $n > 4$) show that the laser pulse self-modulation and efficient generation of accelerating wakefield appears practically identical for the scale lengths $l_x = 1$ μm and $l_x = 15$ μm in (1) as in the case of the 1D3V approximation [10]. Note that the steepening of the leading edge of the laser pulse in the experiment may be due to the ionization nonlinearity [13]. The trapping and acceleration of electrons take place only at the negative density gradient [14] at the rear layer of plasma. This conclusion qualitatively distinguishes the results of three-dimensional modeling from the spatially one-dimensional (1D3V) approximation [10] where the electron trapping in the wake wave occurs at the front layer of plasma, provided that the size of inhomogeneity of the density profile is sufficiently small.

The influence of the plasma density irregularities transverse to the propagation direction of the laser pulse on the process of electron acceleration was simulated by considering the exponential profile $n(y)$ in expression (1) with a characteristic size of inhomogeneity $l_y = 100$ μm,

$$n(y) = \exp(-y/l_y), \tag{2}$$

and with longitudinal variations at the boundaries of the plasma layer $l_x = 15$ μm.

The calculations performed with the Gaussian laser pulse temporal profile and the two-dimensional inhomogeneous density distribution (1), (2) showed that for the considered plasma and laser pulse parameters the plasma wave seed amplitude is not sufficient for the development of self-modulation instability, wakefield generation and acceleration of electrons. In the case of a sharp front edge of the laser pulse for the rectangular or hyper-Gaussian temporal envelope the calculations with two-dimensional inhomogeneous density profile also demonstrate the excitement of the wake wave growing as the laser pulse propagates.

Figure 1 shows the phase plane (x, p_x) and the energy spectrum of electrons emitted from the computational domain in the propagation direction of the laser pulse (p_x >0) at $l = ct = 300$ μm (when the laser pulse leaves the interaction region) for the rectangular temporal envelope of the laser pulse and two-dimensional non-uniform plasma density.

In the case of one-dimensional non-uniform plasma as well as in the case of two-dimensional inhomogeneous plasma the energy at the maximum of the energy distribution is 0.26 MeV (figure 1*b*) and energy distributions are qualitatively similar. The charge of a bunch of accelerated electrons measured at the half-maximum of the energy distribution in both cases equals ∼0.1 nC. The distribution width at the half-maximum for the two-dimensional inhomogeneous plasma is 0.4 MeV, which is slightly higher than the corresponding value of 0.34 MeV for the one-dimensional inhomogeneous plasma. For the hyper-Gaussian temporal shape of the laser pulse with $n = 4$ and the same two-dimensional inhomogeneous distribution of the plasma density the energy distribution is qualitatively the same and the energy at the maximum of the distribution is slightly higher and equals ∼0.3 MeV. Thus, the relative width of energy distribution at half maximum (FWHM divided by the maximum of energy of the distribution) is greater than that in the experiment [10].

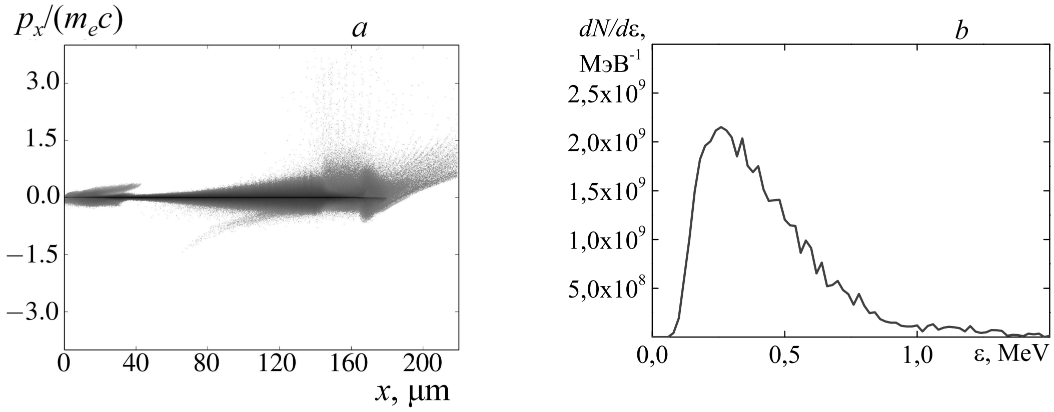
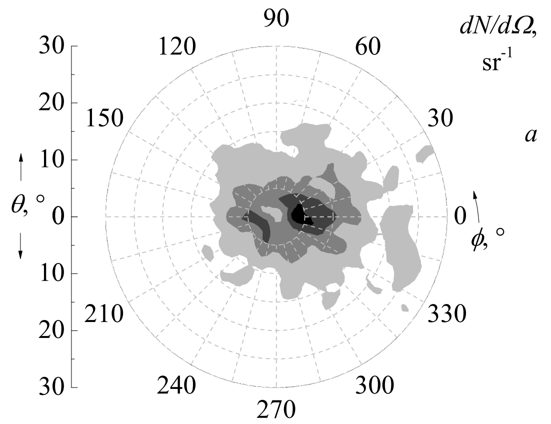


Figure 1. The phase plane (*a*) and energy spectrum (*b*) of electrons emitted from the computational domain in the propagation direction of the laser pulse ($p_x > 0$) at $l = ct = 300$ μm for the two-dimensional non-uniform plasma density and rectangular temporal envelope of the laser pulse.

Figure 2*a* shows the distribution of electrons emitted from the computational domain into a solid angle Ω for the two-dimensional non-uniform plasma density. A polar angle θ of the spherical coordinate system is measured from the positive direction of the OX axis in which the laser pulse propagates, and an azimuthal angle ϕ — from the positive direction of the OY axis along which the plasma density decreases. Twice the width at half-maximum of the angular distribution $\bar{\Omega}^{\phi}$ is 0.3 rad (see figure 2*b*). This distribution is obtained by averaging the distribution in the solid angle over the angle ϕ. Simulations have shown that in the case of the two-dimensional inhomogeneous plasma density distribution accelerated electrons are somewhat more collimated than in the case of a plasma homogeneous along the OY axis.



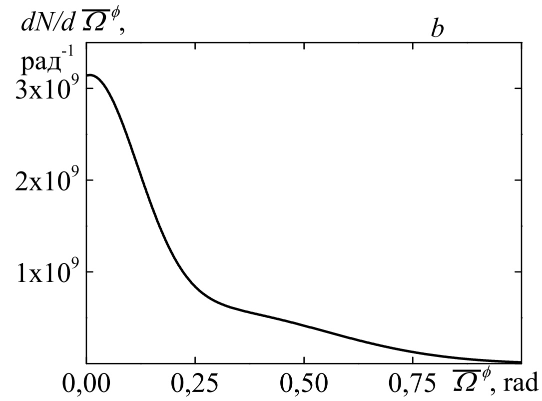


Figure 2. The distribution of electrons in the solid angle $dN/d\Omega$ (a), shown by contours at the equidistant levels with the increment of 8.04×10^8 sr^{-1}; distribution of particles $dN/d\bar{\Omega}^{\phi}$ (b) obtained by averaging the distribution in the solid angle over the angle ϕ (an approximation by two Gaussian distributions). The distributions are shown for electrons emitted from the computational domain in the propagation direction of the laser pulse ($p_x > 0$) at $l = ct = 300$ μm for the two-dimensional non-uniform plasma density.

We have also performed simulations with a smaller characteristic size of inhomogeneity in the transverse direction l_y =25 μm while maintaining all other parameters. In this case, the wave breaking of the plasma wave caused by the self-modulation of the laser pulse happens earlier, but in general, the situation is similar to the calculation with l_y =100 μm (see figure 1).

3. Conclusion

Thus, in the above-described three-dimensional (3D3V) simulations with density profiles (1), (2) with the above specified plasma and laser pulse parameters the energy of electrons at the maximum of the energy distribution of 0.3 MeV is in agreement with the experiment [10]. The obtained spectra of accelerated electrons are characterized by a relatively slow ("temperature") decrease in the region of maximum energies and, consequently, the wider energy and angular distribution than was found in the experiment.

Acknowledgments

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