Electron acceleration under the action of a laser pulse onto ionizing plasma corona

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Abstract. The performed simulations in contrast to the previous studies have shown that the generation of the wake wave in the self-modulational regime, its wavebreaking with subsequent particle injection and acceleration occur for the initially Gaussian envelope of the laser pulse if the processes of tunnelling ionization are taken into account. The self-modulation evolve faster in comparison to the case without ionization because of the abrupt density inhomogeneities which appear at the front edge of the laser pulse because of ionization. These inhomogeneities lead to the three wave character of the resonance modulational instability. The ionization blueshifting of the laser light is observed in the simulations.

1. Introduction
Research programs all over the world include nowadays laser-plasma acceleration of electrons. With the current technology of high power lasers it is already possible to obtain electron bunches with energies exceeding GeV. One of the open questions is a development of a particle injector for such accelerators. To date various schemes of injection were proposed and implemented. For example, electrons can be injected into the wakefield generated by the laser pulse when the second colliding pulse is used in addition to the main pulse [1]. Another method of initial acceleration for subsequent trapping by the main accelerating structure is to use a gas nozzle with the negative plasma density gradient [2]. The possibility of creation of a high-energy electron source at oblique incidence of a laser pulse onto a solid target was considered in [3,4]. Electron source of high intensity can be obtained by using foam [5]. In the experiment [6] the scheme of injector is proposed where the electron bunches appear after the focusing of subrelativistic laser radiation onto the edge of the aluminium foil. To describe the generation of monoenergetic electron bunches with energies 0.2–0.8 MeV 3D PIC simulations of laser interaction with inhomogeneous plasma corona were carried out [7].

The effects of tunneling ionization may play an important role in the interaction. Various processes were previously identified and studied including large- and small-scale plasma structures [8], which may affect the field distribution and scattering characteristics considerably, striations in the electron density behind the laser pulse [9, 10]. Particularly, it was shown [11] that ionization may substantially enhance the amplitude of the wake wave generated by the long in comparison with plasma wavelength laser pulse [11, 12]. Ionization may even trigger the self-modulational instability [13] for the range of parameters where it is impossible without...
ionization [12]. The other important process is ionization refraction [14,15] which can lead to considerable distortions of the laser pulse, to steepening of the leading front of the laser pulse and to faster growth rates of the resonance modulational instability. Ionization modulation [16] and ionization focusing [17] are processes which can occur in the front of the laser pulse as a consequence of the refraction. In comparison to the previous studies [7] the aim of this work is to analyze the effects of tunneling ionization on the wake wave generation for the parameters of the experiment [6].

2. Ionization models

In this section the results of the conducted ionization models comparison are briefly described. Simulations in this work were carried out with the 3D PIC code VLPL [18]. Before the modeling of the experiment [6] the validity of the ionization model implemented in the code VLPL was tested across the model implemented in the code LAPLAC [19] with ionization kinetics described in [20, 21]. In the code VLPL the Monte-Carlo scheme was previously implemented [22] to take into account tunneling ionization. According to this approach, at each time step for each unionized particle the ionization rate \( W(t) \) is calculated. Then the probability for particle to be ionized is \( P(t) = 1 - \exp(-W(t)\Delta t) \) which is approximated by \( P(t) \approx W(t)\Delta t \), for \( W(t)\Delta t \ll 1 \). The code generates a random number \( p \) between 0 and 1. If \( p < P \) then the particle is set to be ionized else its ionization state is not changed.

In the LAPLAC ionization model the dynamics of plasma formation due to tunneling ionization is described by the equations of ionization kinetics for the densities \( N_k \) of ions with ionization states \( k \). In both cases the well-known Ammosov–Delone–Krainov (ADK) formula [23] was used to calculate the ionization rate \( W(t) \).

The initial neutral atom density was chosen so that the electron density of fully ionized He or tenfold ionized Al equals \( n_0 = 10^{17} \text{ cm}^{-3} \). The intensities of the laser pulse interacting with He and Al are \( 10^{16} \text{ W/cm}^2 \) (dimensionless laser field amplitude \( a = 0.085 \)) and \( 3 \times 10^{17} \text{ W/cm}^2 \) \( (a = 0.468) \) correspondingly. The electron density profiles obtained by these two models under the same physical parameters are presented in figure 1 together with the laser field distribution. Densities are normalized to \( n_0 \) and fields are normalized to \( mc\omega/e \), where \( m \) is the electron mass, \( c \) is the speed of light, \( \omega \) is the laser frequency, \( e \) is the absolute value of the electron charge. Good agreement for the two models is observed. Steps in the density profiles with the half of the laser high frequency field as well as large-scale density steps caused by successive ionization of inner atom shells is clearly seen in figure 1. These density variations can serve as a source of a ionization seed for the self-modulation process [12].

3. Parameters for modeling of the experiment

In this section the parameters of the modeling are described. These parameters were used to model the experiment on electron bunches generation from the boundary of a metal foil [6]. In contrast to the previous studies [6,7] the processes of tunneling ionization are taken into account in this work (see the section above). A laser pulse has Gaussian temporal and transversal shapes. The transversal full width at half maximum (FWHM) \( d_{\text{FWHM}} = 29.4 \mu\text{m} \) and the temporal FWHM of the pulse \( T_{\text{FWHM}} = 60 \text{ fs} \) for the laser intensity. The central laser wavelength equals \( 1 \mu\text{m} \) and its intensity is \( 3 \times 10^{17} \text{ W/cm}^2 \) which corresponds to the dimensionless amplitude \( a = 0.468 \).

A simulation box has sizes \( 220 \mu\text{m} \) along the x-axis and \( 150 \mu\text{m} \) along both the y-axis and z-axis. Sizes of a numerical cell are \( 0.05 \mu\text{m} \) along the x-axis and \( 0.5 \mu\text{m} \) along the y-axis and the z-axis. The pulse is linearly polarized along the y-axis and propagates along the x-axis. We consider plasma layers consisting of electrons and three times ionized aluminium ions initially. It is assumed that this ionization state is caused by the action of the prepulse. The plasma is uniform everywhere along the y- and z-axis. The scheme of the normal incidence is studied...
in the work. The plasma has a nonuniform density profile along the x-axis with half-Gaussian drops at the plasma boundaries. The inhomogeneity scale length (exponential half-width) of the boundary layers is \(l_x = 15 \mu\text{m}\). In the region \(0 \leq x \leq 40 \mu\text{m}\), the density increases, while at \(160 \leq x \leq 200 \mu\text{m}\) it decreases. In the region \(40 < x < 160 \mu\text{m}\) the initial plasma density is uniform.

In this region three fold ionized Al density \(n_i\) adopts one of the three values \(0.004n_c\), \(0.0075n_c\) or \(0.015n_c\) in different runs, where the critical density \(n_c = m\omega^2/(4\pi e^2)\). These ion densities give electron densities \(n_e\) equal 0.024\(n_c\), 0.045\(n_c\) and 0.09\(n_c\) if Al ions are ionized up to the sixth degree under the action of the femtosecond laser pulse that is valid in our simulations at the axis of the laser pulse propagation (see figure 1b). The electron density 0.045\(n_c\) is the characteristic experimental density and it is used in the previous simulations [6,7]. For all three densities considered the plasma wavelength is shorter than the laser pulse length \(c\tau_{\text{FWHM}}k_p > 1\) and the occurrence of the self-modulational instability is possible. The number of particles per cell equals 4 for electrons and 1 for ions. Time is counted from the moment when the center of the laser pulse is at \((x, y, z) = (0, 0, 0)\).

4. Results and discussion

The wakefield generation in the resonance modulational regime occurs in our simulations for the Gaussian envelope of the laser pulse taking into account ionization processes (figure 2c, d). In previous simulations [6,7] the wakefield generation was observed only for the hyper-Gaussian or rectangular envelope of the laser pulse. The presence of the resonance modulational instability is explained by the presence of density inhomogeneities in front of the laser pulse due to the ionization process [12] (see figure 1b as an example). These inhomogeneities induce laser field modulations in front part of the pulse (figure 2a, b). Field modulations in their turn increase density inhomogeneities. Thus the feedback is formed and resonance modulational instability evolves.

The pulse is splitted into two parts (see figure 2a, b) since the resonance modulational instability amplification factor in the linear theory is proportional to the distance from the leading edge of the laser pulse [24]. At some distance from the leading edge the amplification factor is sufficient to induce hundred percent laser field modulations. This is the point where the splitting is observed. The point is further away from the leading edge for the lower plasma
The modulus of the Fourier transform of the electric field projections.

Figure 3. However, the amplitude of the anti-Stocks is much smaller than the Stocks amplitude. The small-angle scattering approximation. However, the amplitude of the anti-Stocks is much smaller than the Stocks amplitude.

Figure 2. Normalized electric field projections $eE_y/mc\omega$ (a, b) and $eE_x/mc\omega$ (c, d) distributions at the axis of the laser pulse propagation for the initial ion density $0.0075n_c$ (a, c) and for $0.015n_c$ (b, d) at $ct = 140 \, \mu m$.

The wave number values are normalized to the laser wave number $k_0 = \omega/c$. Density (compare figure 2a and b) since the instability amplification factor is proportional to the plasma density $[24]$.

The resonance modulational instability can be caused by one- or multi-dimensional effects of the density and laser energy redistribution. For initial ion densities $n_i = 0.0075n_c$ and $n_i = 0.015n_c$ the instability has one-dimensional character in the linear theory $[24, 25]$. For the lower initial ion density $0.004n_c$ the instability has mixed character $[24, 25]$.

The process of self-modulation can involve three or four waves. To analyze the type of the instability, spatial spectra of the field distributions were obtained (figure 3). In our simulations, three-wave decay is mainly observed for all densities considered. As an example, in figure 3 spatial spectra of the distributions of electric field projections along the x-axis are shown for laser and plasma waves for the initial ion density $n_i = 0.004n_c$. The peaks is clearly seen in the spectrum at $k/k_0 \approx 0.7–0.9$ (see figure 3a), where $k_0 = \omega/c$. A small-angle scattering approximation is valid for our parameters since $k_pL_\perp \gg 1$ and we did not observe transverse modulations $k_p/k_\perp \approx k_p/L_\perp$. In this approximation the frequencies corresponding to the observed peaks are close to the Stocks wave frequency $\omega - \omega_p$, where $\omega_p = \sqrt{4\pi e^2n_c/m}$.

The wave numbers in the range $(k/k_0 \approx 1.1–1.2)$ are also seen in figure 3a. These wave numbers correspond to the frequency range close to the anti-Stocks wave frequency $\omega + \omega_p$ in the small-angle scattering approximation. However, the amplitude of the anti-Stocks is much smaller than the Stocks amplitude. The small-angle scattering approximation.
Figure 4. Phase plane \((x, p_x/(mc))\) distribution of electrons for the initial ion density \(0.0075n_c\) at \(ct = 180 \, \mu\text{m}\) (a) and for \(0.015n_c\) at \(ct = 140 \, \mu\text{m}\) (b). For the higher distribution values the color is darker.

lower than that of Stocks component. The same features of the Stocks component dominance are observed for higher and lower plasma densities considered. This is not the case in the previous simulations without ionization processes taken into account [7] where both Stokes and anti-Stokes components had almost the same amplitudes for the electron density \(n_e = 0.045n_c\). The difference is due to the difference in seed waves which triggers the resonance modulational instability. In the case without ionization the seed amplitude is generated gradually by the laser pulse. At some distance from the front edge of the laser pulse \(k_p\xi > (\omega_p/\omega_a)^2\), the amplitude is sufficient to trigger the instability via four wave process. In the case with ionization the seed amplitude appears sharply at the distance from the front edge of the laser pulse \(k_p\xi < (\omega_p/\omega_a)^2\) and the three wave decay mechanism is dominant since its amplification factor is higher for small distances. The asymmetry in the Stokes and anti-Stokes component amplitudes may also results from the nonlinear stage of the instability evolution [25] or it can be ascribed to nonstationarity of ionizing medium. The blueshifting of the laser light because of ionization is clearly seen in figure 4a.

In figure 3b the spatial spectrum of the longitudinal projection of the electric field is presented. The form of spectrum is typical of all plasma densities considered. Two main peaks are observed in the spectrum. The first one is at \(k \approx k_p = \omega_p/c = 0.2k_0\). This is the wake wave which is generated during the resonance modulational instability. The second peak observed can be explained by the presence of the transverse wave which spreads at an angle to the axis and has a longitudinal projection of the electric field. The reason is the refraction of the transverse wave which occurs at higher plasma densities caused by higher ionization rates at the axis of the laser pulse propagation. In favor of this explanation is the fact that such a peak is not observed in 1D simulation with the same parameters. The deviation of the wave from the initial direction of the laser pulse propagation can also appear because of the process of the angular scattering.

As a result of the self-modulational instability, wave breaking occurs when the amplitude reaches the value \(eE_x/(mc\omega_p) \approx 1\). The wave breaking is accompanied by injection into the wake wave and by subsequent acceleration of electrons (figure 4). For the higher ion density the instability grows faster (in the linear theory the instability amplification factor is proportional to the density [24]) and as a consequence wave breaking with electron injection takes place earlier in time (compare figure 4a and b).
5. Conclusion
The generation of the wake wave in the self-modulational regime and its wave breaking are observed in the simulations for the initially Gaussian envelope of the laser pulse if the processes of tunnelling ionization are taken into account. Subsequent particle injection and acceleration occur as well. The self-modulational instability evolves faster in comparison to the case without ionization because of the abrupt density inhomogeneities which appear at the front edge of the laser pulse because of ionization. These inhomogeneities lead to the three wave character of the resonance modulational instability. The ionization blueshifting of the laser light is observed in the simulations. The second peak in the spectrum of the longitudinal component of the electric field observed at $k/k_0 \approx 0.8$ is due to the presence of the transverse wave which propagates at the angle to the axis.

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