Effect of laser pulse self-focusing on plasma wave generation in the interaction of subterawatt laser pulse with a plasma jet

To cite this article: V S Popov et al 2019 J. Phys.: Conf. Ser. 1147 012078

View the article online for updates and enhancements.
Effect of laser pulse self-focusing on plasma wave generation in the interaction of subterawatt laser pulse with a plasma jet

V S Popov¹,², L P Pugachev¹,² and N E Andreev¹,²

¹ Joint Institute for High Temperatures of the Russian Academy of Sciences, Ezhorskaya 13 Bldg 2, Moscow 125412, Russia
² Moscow Institute of Physics and Technology, Institutskiy Pereulok 9, Dolgoprudny, Moscow Region 141700, Russia

E-mail: SlavaPopov1991@yandex.ru

Abstract. The wake plasma waves generated by high intensity laser pulses are of interest for acceleration of electrons to high energies. The aim of this work is to study the effect of self-focusing of a laser pulse on the plasma wakefields generation. Calculations were performed using the three-dimensional particle-in-cell method. When the laser pulse in the process of propagation in inhomogeneous plasma reaches the region where the pulse power exceeds a critical value for self-focusing, the laser pulse is self-focused and a steepening of the leading edge of the pulse increases. These processes lead to self-modulation instability and generation of a wake plasma wave.

1. Introduction
In last few years, considerable progress has been made in the field of creating ultrarelativistic electron bunches using ultrashort high-intensity laser. In 2014, a quasi-monoenergetic electron beam with energy of 4.2 GeV was produced with a BELLA laser (Lawrence Berkeley National Laboratory, USA) [1]. In this experiment, the laser power was equal 0.3 PW. The pulse was propagated through capillary discharge waveguide with a rarefied plasma density of \( \approx 7 \times 10^{17} \text{ cm}^{-3} \). In this case, the plasma wave was excited in a strongly nonlinear regime (bubble-regime, which is realized at a dimensionless amplitude of the laser field is much larger than unity \( (a_0 \gg 1) \). Also, such lasers are used with other types of targets for efficient electron acceleration. For example, foam targets with a near-critical density [2] and solid targets [3] are used. However, a laser pulse of this power is available only to a few laboratories around the world. Due to the high demand for high-energy electron beams for a variety of applications, there is a need to create high-energy beams with some much more low-power lasers. The energy of such lasers does not exceed 100 mJ, and such level is available for many modern laboratories. Such sources of high-energy electrons are very necessary for many areas, such as superfast radiography with low radiation dose, substance research, isotope production, and others.

Previous works in this area [4, 5] demonstrates the production of electron bunches up to the energy of 10–12 MeV in a plasma jet using lasers with an energy of less than 100 mJ. The authors of work [5] note that the effect of relativistic self-focusing plays an important role in the process of injection and acceleration of electrons. Also, the acceleration of electrons in an inhomogeneous
plasma with a low-power laser was studied in the works [6–8]. Computational modeling of the effect of ionization effects on the propagation of a laser pulse of low power in an aluminum plasma have also been carried out in [9]. In our work, the influence of the self-focusing effect of the laser pulse on the processes of plasma wakefield generation was investigated. Numerical modeling was carried out using a three-dimensional particle-in-cell code [10].

2. Calculation parameters

The parameters of the laser pulse incident on the plasma in the calculations correspond to the experiment [5]. A laser pulse has Gaussian temporal and transversal shapes. The laser spot size and pulse duration are equal to 9.7 µm and τ = 50 fs respectively. The central laser wavelength equals 1 µm. The laser pulse intensity is $7 \times 10^{17}$ W/cm$^2$ which corresponds to the dimensionless amplitude $\alpha_0 = 0.715$. The energy of the laser pulse is $W = 40$ mJ, and the power of the laser pulse is $P = W/\tau = 0.8$ TW. The pulse is linearly polarized along the $y$-axis and propagates along the $x$-axis. The laser has a plane wave front at the initial time. The plasma is uniform everywhere along the both axes $y$ and $z$ and has a nonuniform density profile along the $x$-axis.

The electron density profile along the propagation of the laser pulse (OX) is specified as follows:

$$n = n_0 \exp[-(x-x_c)^2/l^2],$$

where $x_c = 300$ µm is the center of the computational domain, and the inhomogeneity scale length is $l = 120$ µm. The maximum electron density $n_0$ is equal to 0.059$n_e$, which corresponds to $6.5 \times 10^{19}$ cm$^{-3}$. The critical density $n_c = m\omega^2/(4\pi e^2)$, where $m$ is the electron mass, $\omega$ is the laser frequency, $e$ is the absolute value of the electron charge. A simulation box has sizes 600 µm along the $x$-axis and 120 µm along the both axes $y$ and $z$. The sizes of a numerical cell are 0.05 µm along the $x$-axis and 0.5 µm along the both axes $y$ and $z$. The number of particles per cell equals 4 for electrons and ions. The center of the laser pulse is located at the left border of the computational domain at $x = 0$. At the initial time, the plasma is cold, i.e. $T_e = 0$.

3. Results and analysis

Figure 1 illustrates the dependence of the laser pulse width (full width at half maximum of intensity) on the pulse propagation time. The process of self-focusing of a laser pulse leads to an increase in the intensity of the laser field in the center of the pulse. This is shown in figure 1. Further, the variable $t$ denotes the time of the center of the laser pulse passing from the left border of the computational domain. This time corresponds to the distance $ct$, which passed the center of the laser pulse in vacuum from the left border of the computational domain (variable $c$ is the speed of light). At the beginning of self-focusing ($ct = 180$ µm), the maximum laser field on the axis begins to rise sharply from $eE_y/(mc\omega_0) = 0.6$, and reaches maximum value $eE_g/(mc\omega_0) = 1.6$ at the time $ct = 380$ µm. At the same time, the width of the laser pulse reaches the minimum ($d_{\text{FWHM}} = 3.4$ µm).

When the laser pulse in the process of its propagation in plasma reaches the region where the pulse power exceeds a critical value for self-focusing, the laser pulse is self-focused and a steepening of the leading edge of the pulse increases. The value of plasma density in the area where self-focusing starts is equal to $n_e/n_{ct} = 0.0182$, that corresponds to left dash-dotted line. This density corresponds to the value of the critical power of the pulse, equal to $P_{cr} = P_0n_{ct}/n_e = 956$ GW, where $P_0 = 17.4$ GW. Thus, the ratio of the laser pulse power to the critical power at this point is $P/P_{cr} = 0.84$.

Figures 2–5 show the evolution of the laser pulse and the plasma wave. For four moments of time, which are marked in figure 1 by numbers (the numbers correspond to the figure numbers) the distributions of the $E_y$ field (the laser pulse) and longitudinal $E_x$ field (plasma wave) are demonstrated. Figure 2 shows the moment when the pulse starts to shrink and plasma wave is absent. Further, compression of the laser pulse in the transverse direction and increasing of the
Figure 1. The dependence of the laser pulse full width at half maximum (blue curve), the maximum laser field on the axis (orange curve) on the distance traveled by the pulse from the left border of the area. The dotted line illustrates the distribution of electron density in arbitrary units. Vertical dash-dotted lines indicate the self-focusing area. The numbers correspond to the following moments of time: 2—$ct = 290 \ \mu m$; 3—$320 \ \mu m$; 4—$350 \ \mu m$; 5—$380 \ \mu m$.

Figure 2. Laser wave field $E_y$ distribution (a) and plasma wave field $E_x$ distribution (b) at time $ct = 290 \ \mu m$. 
Figure 3. Laser wave field $E_y$ distribution (a) and plasma wave field $E_x$ distribution (b) at time $ct = 320 \, \mu m$.

Figure 4. Laser wave field $E_y$ distribution (a) and plasma wave field $E_x$ distribution (b) at time $ct = 350 \, \mu m$. 
Figure 5. Laser wave field $E_y$ distribution (a) and plasma wave field $E_x$ distribution (b) at time $ct = 380 \, \mu m$.

Figure 6. Transverse wave field $E_y$ distribution over the laser pulse propagation axis at time $ct = 350 \, \mu m$ and its spatial spectrum. Two lateral satellites are visible, which are spaced from the main peak to the plasma wave vector.
laser field amplitude leads to self-modulation of the pulse. The self-modulation process is well illustrated in figure 3. Also this figure shows the appearance of a plasma wave. Figure 4 shows the decay of a laser pulse into several shorter pulses with a length on the order of the plasma wavelength. Due to strong self-modulation, a regular plasma wave of large amplitude appears, which is shown in figure 4(b). In figure 5, the amplitude of the laser pulse reaches a maximum, and the laser pulse completely lost original form, but the regular plasma wave is still retained, which allows it to be accelerated.

The process of pulse self-modulation is also confirmed on the spectrum of the laser pulse field on the axis, which is shown in figure 6. This picture illustrates the appearance of satellites that correspond to the plasma wave vector at a density equal to \( n_e = 0.05n_{cr} \), for the moment of time \( ct = 350 \ \mu m \) which is marked by point 4 in figure 1. This moment of time corresponds to the developed process of self-focusing.

4. Conclusion
The present study of nonlinear effects arising during the interaction of subterawatt laser pulse with inhomogeneous plasma has shown that the laser pulse self-focusing under experimental conditions [5] has a significant impact on the plasma wave generation process. This effect occurs when the pulse reaches the plasma region where the critical power becomes less than the laser pulse power. Due to the self-focusing of the pulse, it is compressed towards the axis of propagation of the pulse, and its amplitude increases sharply. The regime of interaction of laser pulse with the plasma becomes nonlinear. This leads to the effect of self-modulation of the laser pulse. The pulse is divided into a sequence of shorter pulses with a length of the order of the plasma wavelength. This effect makes it possible to effectively generation the plasma wave in the modulation mode [11, 12], and the amplitude of the plasma wave increases sharply. In the future, the processes of injection and acceleration of electrons in a plasma wave will be studied.

References
[1] Leemans W P et al 2014 Phys. Rev. Lett. 113 245002
[2] Pugachev L P, Andreev N E, Levashov P R and Rosmej O N 2016 Nucl. Instrum. Methods Phys. Res., Sect. A 829 88–93
[3] Andreev N E, Pugachev L P, Povarnitsyn M E and Levashov P R 2016 Laser Part. Beams 34 115–22
[4] He Z H, Hou B, Nees J A, Easter J H, Faure J, Krushelnick K and Thomas A G R 2013 New J. Phys. 15 053016
[5] Goers A J, Feder G A, Miao B, Salehi F, Wahlstrand J K and MIlchberg H M 2015 Phys. Rev. Lett. 115 194802
[6] Pugachev L P, Andreev N E, Levashov P R, Malkov Y A, Stepanov A N and Yashunin D A 2015 Plasma Phys. Rep. 41 542–52
[7] Sylla F, Flacco A, Kahaly S, Veltcheva M, Lifschitz A, Sanchez-Arriaga G, Lefebvre E and Malka V 2012 Phys. Rev. Lett. 108 115003
[8] Malkov Y A, Stepanov A N, Yashunin D A, Pugachev L P, Levashov P R, Andreev N E and Andreev A A 2013 Quantum Electron. 43 226–31
[9] Pugachev L P, Popov V S and Andreev N E 2016 J. Phys.: Conf. Ser. 774 012106
[10] Pukhov A J 1999 Plasma Phys. 41 425–33
[11] Andreev N E, Gorbunov L M, Kirsanov V I, Pogosova A A and Ramazashvili R R 1992 Pis’ma Zh. Eksp. Teor. Fiz. 55 351
[12] Andreev N E, Kirsanov V I, Gorbunov L M and Sakharov A S 1996 IEEE Trans. Plasma Sci. 24 363–9