Characterization of accelerated electrons generated in foams under the action of petawatt lasers

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Abstract. Analytical prediction of accelerated electrons yield from near-critical targets under the action of petawatt laser radiation is complicated with various processes, such as self-focusing and density channel bending. We investigate the properties of accelerated electron beams at fixed parameters of the petawatt laser radiation and the varied target density using three-dimensional “particle-in-cell” simulations. Shown the most advantageous electron acceleration takes place in the density range from 0.5 to 1.0 of the critical density. The use of a smaller laser spot size of 4.25 \( \mu \text{m} \) instead of 25 \( \mu \text{m} \) makes it possible to obtain 30 times more intense electron beams with energies higher than 50 MeV at the same energy of the laser pulse.

1. Introduction

Studies of petawatt lasers interaction with near-critical targets are important for various fields of science. For example, it is necessary to ensure efficient transmission of a laser pulse through near-critical plasma \cite{1} for inertial confinement fusion. Layers of near-critical density materials can be used together with solid targets or as separate targets for ion acceleration \cite{2, 3}.

Electron fluxes with 100s of MeV energies can be generated in the interaction of petawatt lasers with near-critical plasma \cite{4}. A distinctive feature of these fluxes is their high charge, which is a consequence of a high absorption coefficient of laser radiation in the near-critical target \cite{5}. The possibility of using electron beams with such properties, as well as x-rays generated by them \cite{6}, for the diagnosis of various materials is considered.

As shown in \cite{4} considering near-critical densities with three-dimensional (3D) “particle-in-cell” (PIC) simulations, the laser pulse creates a channel in the electron density. An azimuthal magnetic field is generated in the channel. The focusing force associated with the field creates conditions for direct laser acceleration (DLA) of electrons at betatron resonance with the laser field. However, detailed quantitative description of this mechanism has not been provided.

Regarding densities well below the critical density, the focusing force acting in the channel is caused by an uncompensated ion charge. Under these conditions, DLA has been theoretically analyzed in \cite{7}. However, various additional processes take place such as self-focusing and hosing instability which hinder theoretical analysis for higher densities.

Although the channels are formed in the interaction of intense radiation with the near-critical target for laser-plasma parameters considered in \cite{8}, the ponderomotive heating of electrons is
a main accelerating mechanism. As a result, the electron energy distribution is Boltzmann-like and its effective temperature is defined by the self-focused amplitude of the laser field. Direct laser field acceleration produces some effect, but makes a small contribution to resulting electron energies.

In this paper, we extend works [8,9], where the radiation with the PHELIX laser parameters and targets of various types are analyzed. In this work, the laser radiation of the petawatt level with the PHELIX laser parameters and targets with densities in the range from 0.1 to 2.0 of the critical density are studied. In contrast with the previous work [8], the laser radiation with the same power, but with a smaller spot size and a higher intensity is used and the density of the target is varied at fixed target thickness.

The main objective of the work is to obtain quantitative characteristics of accelerated electron beams depending on the target density. Since the interaction of laser radiation with the near-critical density targets causes different physical processes and regimes of acceleration simultaneously it is hard to describe it analytically. We fill the gap in data on high energy electron gain in these conditions using 3D PIC simulations. Electron energy, angular distributions and charges of electrons which left the target are obtained. Based on these data we conclude which parameters are the most advantageous. Possible acceleration regimes are discussed.

2. Method and parameters

For simulating laser–plasma interaction, the PIC method was applied. This method was chosen because it is well-proven in many problems of relativistic laser plasma. Relativistic full-scale parallel 3D PIC method implementation [10] was used in the work.

In simulations, a laser pulse had Gaussian temporal and transversal shapes. The full width at half maximum (FWHM) spot size equaled 4.25 µm and the FWHM duration of the pulse equaled 700 fs. The laser wavelength equaled 1 µm and the laser intensity was $5.67 \times 10^{20}$ W/cm² that corresponds to the dimensionless amplitude $a_0 = cE_L/(me\omega) = 20.35$, where $e$ is the absolute value of the electron charge, $E_L$ is the laser electric field strength, $m$ is the electron mass, $\omega$ is the laser frequency, $c$ is the speed of light. The energy of the laser pulse equaled 120 J. The pulse was thus of the same energy as in the work [8], but with the smaller spot size, larger amplitude and longer duration. The pulse was linearly polarized along the $y$-axis, was propagating along the $x$-axis and was incident normally on the target.

A uniform plasma layer of 500 µm thickness was used. An electron density was varied in four different simulation runs and equaled 0.1, 0.5, 1.0 and 2.0 of the critical density. The critical density $n_{cr} = m\omega^2/(4\pi e^2)$. The plasma was composed of electrons, fully ionized ions of carbon, hydrogen and oxygen. Taking ions in proportion 3 : 4 : 2 allowed the interaction with the triacetatecellulose foam $C_{12}H_{16}O_8$ to be properly modeled. Foam layers of this material have already been used in experiments [11].

Heating and ionization of the foam material were not considered in our simulations. Experimentally, fully ionized CHO plasma layers, hydrodynamically stable over ns time scale, can be created via direct irradiation of the low density foam with the nanosecond laser prepulse of a moderate intensity (few $10^{14}$ W/cm²). In this case, ionization is governed by the supersonic ionization waves, described in [12]. Laser intensity, foam density and foam thickness can be matched in such a way that the velocity of the ionization front will be much faster than the ion acoustic velocity. After propagation of the supersonic ionization wave through the target, the plasma layer does not undergo notable expansion [12].

A simulation box had a size of 610 µm along the $x$-axis. The first 10 and the last 100 µm of the space in this direction were free of the plasma at the initial moment. The box had 80 µm size both along the $y$-axis and the $z$-axis. Sizes of a numerical cell were 0.05 µm along the $x$-axis and 0.5 µm along the $y$-axis and the $z$-axis. The number of particles per cell equaled 4 for the
Figure 1. The electron density (a) and the magnetic field component $b_y$ (b) in the plane $y = 0$ at 2170 fs and for the density of $0.1n_{cr}$.

Figure 2. The electron density in planes $z = 0$ (a), $y = 0$ (b) and the electric field component $e_y$ in the plane $z = 0$ (c) at 500 fs and for the density of $0.5n_{cr}$.

electrons and 1 for the ions of each type. Boundary conditions were absorbing for particles and fields in each direction.

At the initial moment the laser pulse was far away from the target and did not affect it. The pulse was focused to the point $x = 10 \mu m$ at the front surface of the target. Time in the text and figures in the following sections is counted from the moment when the center of the laser pulse was at $x = 0$. 

3. Results

All the electron densities considered in simulations were below the relativistically corrected critical density $\gamma n_{\text{cr}} \approx 14.4n_{\text{cr}}$, where $\gamma = (1 + a_0^2/2)^{1/2}$ is the averaged Lorentz factor. It allowed the pulse to penetrate in the depth of targets. Electrons were pushed out by the ponderomotive force of the laser from the volume where the pulse propagated. As a result, channeling of the laser light was observed. However, channels were different for three electron densities considered.

The channel formed in the density of $0.1n_{\text{cr}}$ had a straight cylindrical shape. Channel axis was directed along the initial propagation axis of the laser pulse, figure 1(a). In all figures are shown fields normalized to $mc\omega/e$ and the density normalized to $n_{\text{cr}}$. At the time of 2170 fs the channel has crossed the whole target. Although the bulk of accelerated electrons were evacuated from the target by this time, there was some current of accelerated electrons in the rear part of the target. The current generated a strong quasistatic magnetic field. A projection of the magnetic field $b_y$ in the $y = 0$ plane. Figure 1(b) indicates its azimuthal structure.

Shapes of channels in plasma with higher densities was not so direct as in plasma with the density of $0.1n_{\text{cr}}$. The channel in the density of $0.5n_{\text{cr}}$ deviated notably from the initial direction.
Figure 5. Angular distributions of electrons, which left the simulation domain with \( p_x > 0 \) and with energies higher than 50 MeV (\( a, b \)) and higher than 125 MeV (\( c, d \)), over the angle \( \theta = \arctan(p_y/p_x) \) (\( a, c \)) and \( \phi = \arctan(p_z/p_x) \) (\( b, d \)) at 2170 fs. Simulation results for densities of 0.1\( n_{cr} \) (black), 0.5\( n_{cr} \) (red), \( n_{cr} \) (blue) and 2\( n_{cr} \) (cyan) are shown.

of the pulse propagation to the side of negative values of \( z \)-axis in the \( y = 0 \) plane, while it was straight in the \( z = 0 \) plane, figure 2(\( a, b \)). While the channel in the density of \( n_{cr} \) bended also, it is relatively straight at the first two thirds of its length, figure 3. The channel in the density of 2\( n_{cr} \) turned to the side of negative values of \( z \)-axis in the \( y = 0 \) plane as well as to the side of positive values of \( y \)-axis in the \( z = 0 \) plane, figure 4. The length of the channel in the density of 2\( n_{cr} \) was approximately two times shorter than those in densities of 0.5\( n_{cr} \) and \( n_{cr} \).

As in paper [8], self-focusing of the laser pulse was observed. For example, the dimensionless amplitude increased to about 30 for the density of 0.5\( n_{cr} \), see figure 2.

Observed angular distributions of accelerated electrons which left the simulation domain correlated with the particular form of the channel, figure 5. Distributions were almost symmetrical as functions of an angle for the density of 0.1\( n_{cr} \) and they were not so for higher densities. Besides, angular distributions were narrower for the density of 0.1\( n_{cr} \) than for the other densities. A maximum of the distribution over the angle \( \phi = \arctan(p_z/p_x) \) shifted to the side of negative angle values for the density of 0.5\( n_{cr} \). In the case with the density of 2\( n_{cr} \), the maximum of the distribution over the angle \( \theta = \arctan(p_y/p_x) \) (over the angle \( \phi \)) shifted to the side of
Figure 6. Energy spectra (a) and charges of electrons with energy higher than the given one (b). Only electrons were counted which left the simulation domain with $p_x > 0$. Simulation results for densities of $0.1 n_{cr}$ (black), $0.5 n_{cr}$ (red), $n_{cr}$ (blue) and $2 n_{cr}$ (cyan) are shown. The ponderomotive scalings with temperatures 6.9 and 10.3 MeV for the 7% deposition of the laser energy in hot electrons are shown by green dash lines.

Energies and charges of accelerated electrons obtained in all four simulations exceeded substantially those obtained with the ponderomotive scaling $T_h = m c^2 ((1 + a^2/2)^{1/2} - 1)$ both for the initial amplitude $a_0$ and for the increased amplitude $a$ of the laser pulse, figure 6(a). The temperature $T_h$ equals 6.9 MeV for the initial amplitude and 10.3 MeV for the increased amplitude due to self-focusing. To estimate this amplified amplitude, the maximum amplitude observed in the calculation for the density of $0.5 n_{cr}$ was taken. The highest maximal energies of accelerated electrons were observed in the simulation for the density of $0.5 n_{cr}$, while maximal energies for densities $n_{cr}$ and $2 n_{cr}$ were slightly lower, see figure 6(a) and table 1. Even lower maximal energies were achieved for the density of $0.1 n_{cr}$.

Charges of accelerated electrons were close for densities of $0.5 n_{cr}$ and $n_{cr}$, figure 6(b) and table 1. In the simulation for the density of $2 n_{cr}$, charges of electrons with energies higher than 50, 100, 150 MeV were lower than those obtained for densities $0.5 n_{cr}$ and $n_{cr}$. Nevertheless, the charge with the energy higher than 0 was the highest for the density of $2 n_{cr}$. Regarding the density of $0.1 n_{cr}$, charges were lower than charges for densities $0.5 n_{cr}$, $n_{cr}$ and $2 n_{cr}$.

4. Discussion
Accelerated electrons possess the Boltzmann-like distribution for the laser-plasma parameters considered in [8]. Their energies are determined mainly by the ponderomotive force of the self-focused laser pulse. Direct laser acceleration can not probably manifest itself at that parameters because electrons left the channel through its side walls shortly after the initial energy gain. This is confirmed by wide angular distributions obtained in [8].

Highly non-temperature energy distributions with energies beyond the ponderomotive ones obtained in our work indicate an increased role of DLA in channels for the laser-plasma parameters considered. While the ponderomotive force pushes electrons mainly to the sides,
Table 1. Maximal energies of electrons $\varepsilon_{\text{max}}$ and charges of electrons with energy higher than the given one for various electron densities $n_0$. $Q_0$, $Q_1$, $Q_2$ and $Q_3$ are charges with energies higher than 0, 50, 100 and 150 MeV, respectively. Only electrons were counted which left the simulation domain with $p_x > 0$.

| $n_0/n_{cr}$ | $\varepsilon_{\text{max}}$, MeV | $Q_0$, $\mu$C | $Q_1$, nC | $Q_2$, nC | $Q_3$, nC |
|--------------|----------------|-------------|--------|--------|--------|
| 0.1          | 164.5          | 10.9        | 190.5  | 55.2   | 3.1    |
| 0.5          | 205.0          | 53.8        | 846.2  | 174.1  | 21.6   |
| 1.0          | 186.5          | 56.9        | 973.8  | 262.5  | 24.8   |
| 2.0          | 192.0          | 89.2        | 723.3  | 118.9  | 8.9    |

the laser force $\vec{v} \times \vec{b}$ pushes electrons mainly forward. The presence of DLA is thus confirmed by the correlation of channels axes with the direction of angular distributions. In addition, angular distributions for densities $0.5n_{cr}$ and $2n_{cr}$ become narrower for higher energies indicating the dominance of direct laser acceleration at these energies.

Maximal electron energies were the highest for densities of $0.5n_{cr}$, $n_{cr}$ and $2n_{cr}$. Charges with energies higher than 50, 100, 150 MeV were the highest and close for densities of $0.5n_{cr}$ and $n_{cr}$. Angular distributions were the narrowest and most stable for the density of $0.1n_{cr}$. However, the charge and the maximal energy was low in this case.

5. Conclusions

In conclusion, optimal electron acceleration resulting in maximum energies and charge was observed for densities in the range from 0.5 to 1.0 of the critical density. The charge of electrons with the energy higher than 50 MeV is approximately 30 times higher the charge of electrons with energy higher than 30 MeV obtained in [8]. This indicates the effectiveness of using a smaller laser spot size to generate intense electron beams with energies of tens of MeV from the foam. Shown using 3D PIC simulations that it is possible to generate electron beams carrying the charge of about 200–250 nC with electron energies higher than 100 MeV. Such beams can be useful for diagnostics of matter states with the high energy density.

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