High-energy-density electron beam generation in ultra intense laser-plasma interaction

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Abstract

By using a two-dimensional particle-in-cell simulation, we demonstrate a scheme for high-energy-density electron beam generation by irradiating an ultra intense laser pulse onto an aluminum (Al) target. With the laser having a peak intensity of $4 \times 10^{23}$ W cm$^{-2}$, a high quality electron beam with a maximum density of $117 n_e$ and a kinetic energy density up to $8.79 \times 10^{18}$ J m$^{-3}$ is generated. The temperature of the electron beam can be 416 MeV, and the beam divergence is only 7.25°. As the laser peak intensity increases (e.g., $10^{24}$ W cm$^{-2}$), both the beam energy density ($3.56 \times 10^{19}$ J m$^{-3}$) and the temperature (545 MeV) are increased, and the beam collimation is well controlled. The maximum density of the electron beam can even reach 180$n_e$. Such beams should have potential applications in the areas of antiparticle generation, laboratory astrophysics, etc.

Keywords: ultra intense laser, plasma, high-energy-density, electron beam

(Some figures may appear in colour only in the online journal)

1. Introduction

High-energy-density physics (HEDP) has attracted great interest recently and has appeared ubiquitously in the inertial confinement fusion (ICF) [1], particle acceleration [2–4], laboratory astrophysics [5–7], etc. For the generation of antiparticles [8, 9], such as positrons, a high-energy-density electron beam is injected into a high Z target. Both the energy and the density of the electron beam are of crucial importance for positrons’ qualities [10]. Inside the dyadosphere of a black hole [11], the energy density can reach $10^{21}$–$10^{28}$ J m$^{-3}$. Extractable energies from a black hole could be the source of some energetic phenomena in universe like jets and gamma ray bursts [12]. The collimation, propagation, and stability of the energetic jets have not been well understood and require better investigation [13]. HEDP state produced by ultra intense laser-plasma interaction provides a potential opportunity to study astrophysics in a laboratory [14, 15]. With the development of strong laser technology, it is possible to obtain extreme laser pulses with an ultra short duration and an ultra intense intensity [16–18]. Currently, a laser pulse with...
an intensity of $10^{22} \text{ W cm}^{-2}$ is available [19] providing that a PW-class laser can be fairly focused [20]. It is expected that more intense lasers could be obtained after the large laser facility is upgraded [21].

Various methods have been proposed to improve the electron beam quality in recent years, including modifying the characteristics of the laser pulses [22], improving the structure of target [23], as well as other technologies [24, 25]. An electron jet with a density of $10^{20} \text{ cm}^{-3}$ and an energy density up to $7 \times 10^{15} \text{ J m}^{-3}$ is generated [20] whilst a laser of $10^{22} \text{ W cm}^{-2}$ interacts with the near critical density hydrogen plasmas located in a gold cone. This energy density is four orders higher than the threshold for HEDP ($10^{14} \text{ J m}^{-3}$). Another way to generate a high-energy-density electron beam is through the laser wake field acceleration (LWFA) [5, 26]. The self-generated fields in the bubble can focus electrons to several $n_e$ [5] and accelerate them to high energy levels. Since previous investigations were mainly carried out with laser intensities lower than $10^{22} \text{ W cm}^{-2}$, the plasma density is usually two orders lower than the critical density. For a higher laser intensity, a new target should be designed to match with it. For example, we have simulated that a laser with a peak intensity of $10^{23} \text{ W cm}^{-2}$ interacts with low-Z plasma targets (H, CH or He). No bubbles are generated under any densities, but there is an opening hole. However, big bubbles are generated in over critical density plasma as an Al plasma target or even high Z elements (Cu, Au) are employed. This may be due to the fact that under extreme laser intensities, high Z ions with more positive charges can provide a strong electrostatic force to constraint the electrons. Besides, the effect of quantum electrodynamics (QED) on the generation of the high energy electron beam is usually not considered in the previous studies, which should not be ignored as the laser intensity is ultra intense [27].

In this paper, a scheme for generating high-energy-density electron beam through ultra intense laser interacting with $5n_e$ plasmas is proposed. Interaction of a $10^{23} \text{ W cm}^{-2}$ class laser with a $5n_e$ Al plasma target is studied by a relativistic particle-in-cell (PIC) code EPOCH, which has taken into account the strong nonlinear QED effect [28, 29]. The maximum density of the electron beam is up to $117n_e$, and the energy density reaches $10^{18} \text{ J m}^{-3}$, which is seven orders higher than the HEDP threshold. This electron beam may be used in the areas of proton acceleration [30], antiparticle generation, laboratory astrophysics, etc. The paper is organized as follows: section 2 describes the simulation setup, section 3 presents the 2D simulation results and discussions, and finally, we state the conclusions.

2. Simulation model

In this simulation, a circularly polarized laser with a Gaussian profile is incident from the left boundary and propagates along $x$ axis. It has a wavelength of $\lambda_0 = 1 \mu\text{m}$ and a spot radius of $r_0 = 3\lambda_0$, whose full width at half maximum (FWHM) is 30 fs. The intensity of the laser is $4 \times 10^{20} \text{ W cm}^{-2}$, corresponding to a dimensionless maximum amplitude of the laser electric field $a_0 = \sqrt{\frac{1}{274 \times 10^m}} = 382$. With such a high intense laser, the QED effect is significant [31], and is considered in our simulations. The plasma target is initially located between $x = 0$ and $x = 30\lambda_0$. The target is fully ionized and is composed of $\text{Al}^{13+}$ and electrons, whose initial temperature is set to 0.1 keV. The initial target density is $n_e = 1.1 \times 10^{21} \text{ cm}^{-3}$ is the critical density. The simulation box is 40$\lambda_0 \times 20\lambda_0$ with 1024 $\times$ 512 cells. 70 particles are set in each cell, with 5 $\text{Al}^{13+}$ ions and 65 electrons. To see the influence of laser intensity on the electron beams, simulations with different laser peak intensities are also carried out with all other parameters unchanged.

In the text, the effective temperature of the electron beam is calculated with the following formula,

$$T = \frac{E}{n_e} \log (e)$$

(1)

Where $E$ and $n$ are energy and electron numbers, respecting a dot in the electron energy spectrum. Here, we sample two dots to calculate the slope of the steady declining part of the spectrum. To calculate the beam divergence, we can average the divergence angle of each electron in the beam, which is estimated up from the following formulas,

$$\theta = \frac{1}{N} \sum_{i=1}^{N} \theta_i$$

(2)

Where $\theta_i = \tan^{-1}\left(\frac{P_y}{P_x}\right)$, $N$ is the total number of electrons in the beam, $P_x$ and $P_y$ are momentum component in $x$-direction and $y$-direction, respectively.

3. Simulation results and discussions

Figure 1 shows distributions of electron density and electron kinetic energy density. One can see that when the laser field irradiates the target front surface, electrons are accelerated and pushed aside by the ponderomotive force. It can be seen that a big bubble is generated as the laser pulse propagates in the plasma at $t = 27T_0$ (not shown for brevity), where $T_0 = \lambda_0/c$ is the laser cycle. As the laser pulse propagates into the plasma, the number of injected electrons increases. An electron beam with high density, high energy density, and narrow beam diameter is generated at $t = 38T_0$ in the bubble, propagating with the bubble along $x$ axis. Note that in figure 1(a), the injected electrons oscillate strongly in the bubble. The high-energy-density electrons are mainly focused in the bubble especially around the $x$ axis, as shown in figures 1(a) and (c). When the laser front penetrates through the target back, the bubble breaks. At $t = 60T_0$, the electron beam still maintains a fair shape and keeps high density and energy density. The maximum density of the electron beam is about $117n_e$ with an energy density up to $8.79 \times 10^{18} \text{ J m}^{-3}$. The beam is $15\lambda_0$ in length, while the beam width is less than $\lambda_0$, as shown in figures 1(b) and (d). Roughly estimating, the charge of the beam could be 30–300 nC.
For more details, figure 2 shows the evolution of the maximum density of the electrons in the simulation box. The density reaches a peak quickly at the beginning of the laser-plasma interaction. As the laser intensity declines, the density falls down. Before the bubble breaks, the maximum density locates at the laser front. As the data is counted every laser cycle, the evolution line is not so smooth. Besides, the maximum density in the laser-plasma interaction interface is not stable. The maximum density locates in the beam after the bubble breaks at $t = 38T_0$. The maximum density of the beam can maintain $117n_c$ as it propagates through the target at $t = 60T_0$, which is about 23 times that of the initial target density $5n_c$. It is indicated that the electron beam is strongly compressed. The divergence of the electron beam is about $30^\circ$ at $t = 27T_0$, and it decreases to $13^\circ$ as the beam propagates forward at $t = 38T_0$, as shown in figure 2(b). At $t = 60T_0$, the divergence is only about $7.25^\circ$. Figure 2(c) shows the energy spectrum of the beam at $t = 38T_0$. It is shown that the electron energy can reach several GeVs due to acceleration by the laser. However, most electrons are at a low energy level. At $t = 60T_0$, the effective temperature of the beam is 416 MeV by calculation with the formula (1).

In order to understand how the electron beam is being accelerated and collimated, figure 2(d) shows the distribution.
of the longitudinal electric field $E_x$ at $t = 38T_0$, and the profile of $E_x$ at $y = 0$ along the laser is also presented. Here, the laser field has already been cancelled out by averaging it every laser cycle. It can be seen that a peak with positive $E_x$ value appears in the front of the laser pulse. At the back of the laser beam, the bubble with negative $E_x$ value contributes to the acceleration of electrons. The decelerative field in the front of the bubble is longer than the accelerative field. When electrons are accelerated to a high speed, they run into the decelerative field and lose speed. It is of course undesirable for the beam acceleration. Besides, there are still many electrons continuously injecting into the bubble with low energy which take up a great proportion of the injected electrons [32, 33]. That is why most electrons are at a low energy level. Figures 3(a) and (b) show magnetic field $B_z$ and the electric field $E_y$, $t = 38T_0$. The black lines in the figure present the profile of the corresponding field distributing along y direction at $x = 12\lambda_0$. The fields $B_z$ and $E_y$ upper and down the x axis have an opposite direction. Electron’s motion equation is

$$\gamma m \frac{dv}{dt} = -e ( \vec{E} + \frac{v}{c} \times \vec{B} )$$

where $\gamma$ is the Lorentz factor, $c$ is the speed of light, $\vec{E}$ and $\vec{B}$ are the field each electron experiences, and $m$, $e$, and $v$ are parameters of each electron. When laser propagates in the plasma target, the electrons are pushed aside by the ponderomotive force and a big bubble is generated. Electrons rotate under the Lorentz force $\frac{v}{c} \times \vec{B}$. Some electrons move along the inner wall of the bubble, and inject into the bubble from the tail of laser pulse. When injected, the electrons in the beam propagate along x axis as their directions are also modified by the Lorentz force $\frac{v}{c} \times \vec{B}$. When the electrons in the beam moving down to minus y direction, the Lorentz force pulls them back to the axis. And it is similar while electrons moving up to y direction. What’s more, due to the magnetic field $B_z$, electrons are compressed with a very small beam width, and the divergence also gets smaller and smaller.

To check that the electrons move along the bubble inner wall and are injected to generate a beam, figures 3(c) and (d) show current density distributions in the transverse and longitudinal directions at $t = 38T_0$. From the labels above, the transverse current density $J_x$ is one order higher than the longitudinal current density $J_y$. The current density $J_x$ in the middle of the bubble is negative, while that at the two sides of the beam are positive. This means that the electron beam travels along the laser’s propagation direction. For the same reason, electrons at the edge of the bubble reflect back. The current density $J_x$ of the beam at $x = 12\lambda_0$ can reach $-2.3 \times 10^{19}$ A m$^{-2}$ at $t = 38T_0$. From the current density $J_x$, electrons on the edge of the bubble at different side of the x axis travel towards the x axis (figure 3(d)). From the trajectory of the electrons, they just rotate along the bubble inner wall when pushed away from the bubble to the edge, and inject back into the bubble from the tail, contributing to the high density beam. Once injected, the electrons are accelerated directly along the x axis. The high energy density of the beam attributes to both the high beam density and high electron energy.

A series of simulations are carried out to see the influence of laser intensity on the beam generation. All parameters are kept the same as above save the laser peak intensity. Tables 1 (a)–(e) show the main results of these simulations at $t = 60T_0$. As the laser intensity increases, both the maximum density and effective temperature of the electron beam increased significantly. Under an intensity of $10^{24}$ W cm$^{-2}$, the final maximum density of the beam is about $180n_c$, and the effective temperature is 545 MeV. This indicates that a higher laser intensity is beneficial for the beam compression and acceleration. This is due to the fact that the higher the
laser intensity is, the stronger the self-generated field is. Due to the increase of the beam density and the effective temperature, both the current density and the energy density increase, and the energy density is about $3.56 \times 10^{19} \text{J m}^{-3}$ at $t = 60T_0$. At the same time, it is found that the beam collimation is well controlled.

For reference, we also investigate the influence of plasma length on beam generation. When increasing the length of the target without changing the other parameters (see case (f)), the length of the bubble increases as the laser propagating forward, as shown in figure 4(a). From table 1, both the effective temperature and the energy density are higher than the case of thin target at $t = 60T_0$. That is due to the increase of bubble length in the larger target, while the bubble breaks up in the thin target case at about $t = 38T_0$. Electrons are accelerated to run out of the target, resulting in an enhancement of the sheath electrostatic field at the target back which pulls back the electrons. On the contrary, this field is not generated in the case with a larger target. So the injected electrons can be accelerated by the acceleration phase $E_x$ continually. As the laser propagates forward in the larger target at $t = 80T_0$, the beam profile is well maintained. Both the electron density and the energy density are still highly focused in the beam, as is showed in figures 4(a) and (b).

4. Conclusions

To summarize, the interaction of $4 \times 10^{23} \text{W cm}^{-2}$ class laser and Al plasma target is investigated by PIC simulations. A high-energy-density electron beam is generated, whose beam width is $\sim \lambda_0$ and beam length is $\sim 15\lambda_0$. The energy density is higher than $10^{18} \text{J m}^{-3}$, with a beam effective temperature of several hundred MeVs. The divergence of the beam is about $7^\circ$. As the laser peak intensity increases, both the effective temperature and the energy density of the beam increase significantly, while the beam collimation is well controlled. This scheme greatly improves the quality of
electron beam, which could have potential applications in the areas of antiparticles generation, laboratory astrophysics, new radiation source, etc.

References

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