High-flux electron beams from laser wakefield accelerators driven by petawatt lasers

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Abstract
Laser wakefield accelerators (LWFAs) are considered to be one of the most competitive next-generation accelerator candidates. In this paper, we will study the potential high-flux electron beam production of an LWFA driven by petawatt-level laser pulses. In our three-dimensional particle-in-cell simulations, an optimal set of parameters gives ~40 nC of charge with 2 PW laser power, thus ~400 kA of instantaneous current if we assume the electron beam duration is 100 fs. This high flux and its secondary radiation are widely applicable in nuclear and QED physics, industrial imaging, medical and biological studies.

Keywords: laser accelerator, petawatt laser, high-flux electron beam

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

1. Introduction

Ever since its invention, the laser wakefield accelerator (LWFA) has been regarded as one of the best candidates for next-generation accelerators [1]. Compared with conventional radio frequency (RF) accelerators, the advantage of the LWFA is its much larger acceleration gradient and thus more compact size if the same output energy is required [2]. Since 2004, thanks also to the development of high-power femtosecond laser technologies, the output beam quality of the LWFA has been approaching that of the RF accelerator [3–7], making it widely interesting for applications in a variety of fields. Apart from the high energy (GeV level) and low-energy spread (~1%) requirements of some applications, large electron flux is one of the most widely demanded characteristics of accelerator output beams [8]. In particular, for nuclear or QED-related research, large amounts of electron flux can greatly increase the yield of products within a certain time duration, while neither high electron beam energy nor a low-energy spread is required. It has been reported that about 20 nC charged electron beams can be produced by 100 TW level lasers [9]. However, this report was based on the transverse profile complexity of the laser beams. For simple Gaussian mode lasers, the dependence of the output charge number with the laser power and plasma density has not been studied comprehensively yet.

In this paper, we study the potential for generating a high-flux electron beam using petawatt-level laser pulses in LWFAs with a three-dimensional (3D) particle-in-cell (PIC) simulation method. It is found that there is a threshold peak power \( P_{th} \), and that with the laser peak power \( P > P_{th} \) the laser energy can be transversely well confined in the plasma, while for \( P < P_{th} \) the laser spot size increases continuously. \( P_{th} \) correlates negatively with the plasma density \( n_p \) and is similar to the relativistic self-focusing power [10–13]. However, in the current paper \( P_{th} \) has been obtained from 3D PIC simulations, which consider the influence of both relativistic mass increase and plasma cavitation effects. In addition, the curve of the charge number of the output electron beam versus the laser peak power is found to have a transition at \( P_{th} \). This gives us an optimal choice of laser peak power for the maximum average current output.

2. Analytical discussions

In current technologies, high-power laser beams can reach peak power at the petawatt level. If we assume a perfect Gaussian
Figure 1. A schematic view of the laser wakefield accelerator with the laser focus located in front of the plasma region. The plasma density has a flat-top from \( x = 0 \) to \( 2450 \) \( \mu \)m, and for \( x < -100 \) \( \mu \)m or \( x > 2550 \) \( \mu \)m there is a vacuum. Between the vacuum and the plasma density flat-top, there are density transition regions with the \( \sin^2 \) profile. The laser has a simple Gaussian mode with a waist of \( W_0 \) and is focused at \( x_0 = -100 \) \( \mu \)m in the vacuum region on the left, and when it arrives at \( x_1 = 0 \) \( \mu \)m, its spot size increases to \( W_1 \). During its propagation in the plasma region, the laser can be confined due to the self-focusing effect, and excites the wakefield to accelerate the electron beams (not shown in the figure). After exiting the plasma region, the laser diverges and the electron beams come out with high energies. The plasma electrons are ionized from pure nitrogen gas up to a \( 5^+ \) charge state by the laser pre-pulses, and the remaining \( K \)-shell electrons of \( N^5+ \) can be captured by the wake via the ionization injection process.

profile for the laser beam, it has the relation \( P [GW] = 21.5 (aW/\lambda)^2 \), where \( P \) is the peak power, \( a \) is the normalized peak laser vector potential, \( W \) is the spot size factor of a Gaussian beam, and \( \lambda \) is the wavelength [2]. For the purposes of high charge number production, we need a relatively large laser spot size [14], and to drive a highly relativistic wake, \( 1.5 < a < 2.5 \) is good enough for ionization injections [13, 15–24]. Thus, \( W \) can be \( \sim 100 \) \( \mu \)m for a 800 nm wavelength petawatt laser beam. Meanwhile, replacing the laser focusing system is difficult and expensive in experiments, if we want to change the laser power but keep \( a \) unchanged. The solution is that we use a fixed focusing system to focus the laser to a smaller waist size \( W_0 < W \), and place the plasma entrance a distance after the focal spot, so that when the laser reaches the plasma, it has \( a \approx 2 \).

Our configuration is schematically shown in figure 1. The blue region shows a plasma with a density of \( n_p \) which is either pre-ionized or ionized by a laser pre-pulse from nitrogen gas, while the white region is a vacuum. There are transition regions between the vacuum and the plasma at both the front and rear sides. The high-power laser beam is focused at some place before the plasma region \( (x_0 < 0) \) with the focal waist \( W_0 \), so that when the laser reaches \( x_1 = 0 \) the spot size factor \( W_1 > W_0 \) and the normalized laser vector potential \( a_0 = 2 \). With simple calculations, one may find that \( W_1 = \sqrt{P [GW]/21.5 \times \lambda/a_0} \), \( x_0 = x_1 - 0.8 (W_1/W_0)^2 - 1 \), where \( x_0 = \pi W_0^2/\lambda \) is the Rayleigh length.

In weakly relativistic cases \( (a \ll 1) \), the plasma density response is thus negligible, the laser profile evolves according to equation [10]

\[
\frac{d^2}{dx^2} W = \frac{\lambda^2}{\pi^2 W^3} \left( 1 - \frac{\omega_p^2 a^2 W^2}{32e^2} \right) = \frac{\lambda^2}{\pi^2 W^3} \left[ 1 - \frac{P}{P_c} \right].
\]

where \( P_c \equiv \frac{8 \pi m_e c^3}{e^2 \nu_0^2} \approx 17.4 \frac{\pi}{W} [GW] \) is the relativistic self-focusing critical power of a laser beam in plasma, \( \omega \) is the laser frequency and \( \omega_p \) is the plasma frequency. If we assume \( P/P_c \) to be constant during the propagating process—i.e. the plasma density is constant and the energy loss of the laser beam is negligible—the evolution of the laser spot size can be solved with certain initial conditions. For example, if \( W = W_0 \) and \( \frac{d}{dt} W = 0 \) at \( x = 0 \), \( W \) monotonically increases for \( x > 0 \) in the case \( P < P_c \), and \( W \) monotonically decreases for \( x > 0 \) in the case \( P > P_c \). This initial condition corresponds to the situation in which the laser is focused at the vacuum–plasma boundary, and \( W_0 \) is the laser beam waist. However, if we focus the laser before the vacuum–plasma boundary, with a waist of \( W_0 \), one can achieve the same effect as focusing the laser beam at the vacuum–plasma boundary with a waist \( W_{\text{max}} \), asserting \( P > P_c \). This is a very useful method for achieving a suitable effective laser spot size without replacing the focusing system in real LWFA facilities.

3. Simulations

Section 2 discussed the laser profile evolution if the laser is focused before entering the plasma region, using the weakly relativistic model. However, the actual laser profile function can be different from equation (1), especially in the situation \( a \gtrsim 1 \), i.e. the density modification is not negligible. In particular, when \( a \gtrsim 2 \), the laser beam blows the plasma electrons out of the central region and leaves an electron-vacant region, but the ions are still almost stationary because of their much smaller charge-mass ratio compared with electrons. This is called the blowout regime or ‘bubble’ regime. In this regime, the actual self-focusing power is much higher than that in the weakly relativistic model, and is more difficult to calculate analytically. We performed 3D PIC simulations with the code EPOCH [25] to study the laser spot size evolution in this regime. We chose two plasma densities, and the results are shown in figure 2. The simulation box has a longitudinal dimension of 70 \( \mu \)m, and a transverse dimension of 6\( W_l \times 6\( W_l \) (this varies from case to case, so that the laser beam can be well limited in the simulation box, and the transverse resolution is enough for the spot size at the same time). The simulation resolution is fixed to 1024 \( \times 128 \times 128 \), and the simulation time step \( \Delta t \) is set to be very close, but a little bit smaller than the Courant condition requirement. In the plasma region, the number of macro-particles per cell is four for the plasma electrons and \( N^{5+} \), and the background positive charge automatically neutralizes the total charge due to the simulation algorithm. The density of \( N^{5+} \) is \( n_{N^{5+}} = n_p/5 \), where \( n_p \) is the plasma density, thus all the plasma electrons from the pure nitrogen
gas are ionized by the laser pre-pulse. The plasma profile is schematically shown in figure 1, and the laser is focused at \( x = x_0 < 0 \), so that when it reaches \( x = x_1 = 0 \), the normalized vector potential is \( a = a_1 = 2 \).

Figures 2(a) and (b) show the cases with \( n_p = 2 \times 10^{18} \text{ cm}^{-3} \) and \( 4 \times 10^{18} \text{ cm}^{-3} \), respectively. One should notice that the plasma only exists in the region \(-0.1 \text{ mm} < x < 2.55 \text{ mm}\), thus the rightmost dot of each curve is actually outside the plasma region. One can see that the threshold power \( P_{th} \) for the good confinement of the laser beam (i.e. \( W \) decreases monotonically in the plasma region) is (a) 4 PW \( \leq P_{th} < 8 \) PW for \( n_p = 2 \times 10^{18} \text{ cm}^{-3} \) and (b) 2 PW \( \leq P_{th} < 4 \) PW for \( n_p = 4 \times 10^{18} \text{ cm}^{-3} \). For \( P > P_{th} \), the laser spot size changes from \( W_0 \) to \( W_1 \) in the vacuum region, and then changes from \( W_1 \) to \( W_{\text{max}} \) in a very limited region after entering the plasma, and this process is hardly observable in these plots. We cannot observe the oscillation of \( W \) because the plasma region length is smaller than the oscillation period. The \( W \) oscillation period is related to the Rayleigh length \( L_R = \pi W_{\text{max}}^2 / \lambda \), which has a range from 3.5–450 mm in our simulations, while the length of the plasma is just 2.55 mm. This is also the reason why this \( R_{th} \) is different from the ponderomotive defocusing threshold power or the self-focusing upper-limit [26, 27], which is the threshold power for several Rayleigh length ranges.

Then we study the charge number of the output electron beams in all the above cases. Figure 3(a) shows the output electron beam charge numbers with the change of \( n_p \) and \( P \). One may see that for \( n_p = 2 \times 10^{18} \text{ cm}^{-3} \), the charge varies approximately in proportion to \( P^m \) (\( m > 0 \)) with the transition at \( P = P_{th} \approx 2 \) PW, where for the \( P < P_{th} \) cases, \( m > 1 \), and for the \( P > P_{th} \) cases, \( m < 1 \). Meanwhile for \( n_p = 4 \times 10^{18} \text{ cm}^{-3} \) the transition is at \( P = P_{th} \approx 4 \) PW. In the current discussion \( R_{th} \) is the same as the power threshold in the discussion of figure 2.

We assume that in a certain femtosecond laser facility, the average laser power is constant, i.e. \( P_{avg} = P \tau f = \text{const.} \), where \( P \) is the peak laser power, \( \tau \) is the FWHM time duration of one laser pulse, and \( f \) is the laser repetition rate. The average output electron beam current becomes \( I_{avg} = q \tau f \sigma_{avg} / \tau \propto q / P \) if we also assume \( \tau \) does not change with \( P \), where \( q \) is the output charge number within one shot. Thus we conclude that the maximum \( I_{avg} \) is achieved when \( q / P \) reaches its maximum. By looking at figure 3(a), one can find that the \( q / P \) reaches its maximum at the transition \( P = P_{th} \). Consequently, we conclude that the optimal peak power for the maximum electron flux is \( P = P_{th} \). The reason can be explained as follows: when the laser peak power equals the threshold power \( P_{th} \) for laser beam confinement, the transverse size of the laser almost does not change, so the charge accumulation section does not change [14]. This case has a stable charge accumulation rate and has the most efficient charge injection per unit laser power. If \( P < P_{th} \), the laser spot size increases during the propagation process and the laser peak amplitude decreases. When the laser peak amplitude drops below the ionization injection threshold (\( \theta_{th} \approx 1.8 \) for 800 nm lasers), the charge accumulation stops; and if \( P > P_{th} \), the laser spot size decreases during the propagation process, thus the charge accumulation section is reduced, and consequently the charge accumulation rate is reduced.

The energy spectra of the output electron beams for the cases \( n_p = 2 \times 10^{18} \text{ cm}^{-3} \), \( P = 4 \) PW and \( n_p = 4 \times 10^{18} \text{ cm}^{-3} \), \( P = 2 \) PW are shown in figure 3(b). We can see that for the red line case (lower power and higher density), more electrons are concentrated in the low-energy region compared with the black line (higher power and
lower density). This makes the red line case more advantageous for nuclear applications requiring \(\sim 10\) MeV level radiation [8]. Figures 3(c) and 3(d) are the electron beam snapshots when the beams have just exited the plasma region. Figure 3(c) corresponds to the black line case and 3(d) corresponds to the red line case in figure 3(b). One can see a few bunches of electron beams in the snapshots. These bunches are from the different bubbles of the laser wakefield.

4. Conclusions

We have studied the charge number production of petawatt level LWFAs with single Gaussian profile laser beams. We found that there is a threshold laser peak power \(P_{th}\) for laser beam confinement, and \(P_{th}\) is related to the plasma density. We also found that the cases with laser peak power equal to \(P_{th}\) have the most efficient charge injection, and thus can produce the optimal output beam flux. Approximately 10 to 100 nanocoulomb of charge can be produced by the LWFA with a single petawatt laser pulse.

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