High density ultrashort relativistic positron beam generation by laser-plasma interaction

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Abstract

A mechanism of high energy and high density positron beam creation is proposed in ultra-relativistic laser-plasma interaction. Longitudinal electron self-injection into a strong laser field occurs in order to maintain the balance between the ponderomotive potential and the electrostatic potential. The injected electrons are trapped and form a regular layer structure. The radiation reaction and photon emission provide an additional force to confine the electrons in the laser pulse. The threshold density to initiate the longitudinal electron self-injection is obtained from analytical model and agrees with the kinetic simulations. The injected electrons generate γ-photons which counter-propagate into the laser pulse. Via the Breit–Wheeler process, well collimated positron bunches in the GeV range are generated of the order of the critical plasma density and the total charge is about nano-Coulomb. The above mechanisms are demonstrated by particle-in-cell simulations and single electron dynamics.

Introduction

High power laser facilities have achieved great progress since the invention of the CPA techniques [1]. Laser intensities up to $10^{22}$ W cm$^{-2}$ have been realized [2] and the forthcoming installations are expected to reach $10^{23}$–$10^{24}$ W cm$^{-2}$ or even higher [3, 4]. At these intensities, some physical processes such as radiation reaction and gamma photon emission come into play [5, 6]. It is also close to the threshold of quantum electrodynamics (QEDs) effects, where the emitted photon momentum becomes comparable to the momentum of the emitting electron [7]. The radiation effect in the interactions between such high intensity laser pulses and plasmas have been attracting attention for years [8–14].

In this paper, a regime of positron creation due to the electron self-injection and trapping inside the laser pulse is investigated. The schematic is shown in figure 1, which displays the result from a 3D particle-in-cell simulation. Accumulation of the electrons at the head of the pulse generates a strong electrostatic potential which overcomes the ponderomotive potential of the laser and electrons are longitudinally self-injected into the laser pulse. The radiation reaction and photon emission in the longitudinal direction provide an additional force to slow down the electron motion against the laser pulse. Ji et al [15] proposed a radiation-reaction trapping effect where the transverse momentum conservation is employed to explain the electron confinement in the laser pulse. In our work, the longitudinal injection and trapping are considered. Although the electron self-injection is obtained in both QED and NonQED cases, the trapping and modulation only occur with the QED effect. A large number of $\gamma$-photons, which counter-propagate to the laser pulse, are generated by the injected electrons. The photons colliding with the strong electromagnetic field generate the $e^+e^-$ pairs by the multiphoton Breit–Wheeler process [16, 17]. High energy, high density and well collimated positron bunches are the results.

Simulation setup

The simulations are performed with the relativistic electromagnetic code EPOCH [18, 19] in two and three spatial dimensions. A linear–polarized Gaussian pulse with the peak intensity of $10^{24}$ W cm$^{-2}$ propagating...
along the x-axis is focused onto the left edge of the target. The normalized amplitude is \( a_0 = eE_0/m_e\omega \approx 850 \), where \( E_0 \) and \( \omega \) are the laser electric field strength and frequency, \( e \) and \( m_e \) are the electron charge and mass, respectively; and \( c \) is the speed of light in vacuum. The pulse duration is \( \tau = 15 \) fs and the spot size (FWHM) is about 3 \( \lambda \). The laser wavelength is \( \lambda = 1 \) \( \mu \)m. The hydrogen plasma has the peak density of \( n_0 = 4 \times 10^{22} \) cm\(^{-3} \), where \( n_e = m_e\omega^2/4\pi\varepsilon_0^2 \) is the plasma critical density. The simulation box has the size of 35 \( \lambda \) \times 40 \( \lambda \) \times 12 \( \lambda \) in the x, y, and z direction, respectively. The longitudinal density profile linearly increases from 0 to 4 \( n_e \) for \( 10 \lambda < x < 12 \lambda \), remains constant for 20 \( \lambda \), and then linearly decreases to 0 in 2 \( \lambda \). The mesh size for the 2D simulation is \( \delta x = \delta y = \lambda/100 \). The timestep is 0.006 \( T_0 \), where \( T_0 \) is the laser period. All the quasiparticles (16 per cell) are initially at rest. QED effects for nonlinear Compton scattering and multiphoton Breit–Wheeler process are included in the simulations.

Longitudinal electron injection and radiation trapping

With such a high intensity laser, the initially overdense plasma becomes relativistically transparent [20, 21]. The electrons are expelled both longitudinally and transversely by the strong laser ponderomotive force. The laser and plasma parameters here are close to the case of highly relativistic laser-piston regime as discussed by Schlegel et al [22] and Esirkepov et al [23]. The accumulated electrons form a spike in front of the laser pulse and the corresponding density distribution is also similar to the scenario shown in [22, 23]. In this regime, the laser group velocity is replaced by the piston velocity, which is theoretically \( v_f = \beta c \approx 0.875c \) according to our parameters as discussed in [22]. The phase velocity of most part of the laser pulse is \( c \), because most of the pulse is in a bubble with only few electrons inside. By assuming that the laser pushes the electrons like a piston, the accumulated electron density can be estimated as: \( n_p \approx \int_{0}^{T_0} n_0 dl/\delta s \approx \int_{0}^{T_0} v_f n_0 dt/\delta s \), where \( l = v_f t \) is the propagation distance and the characteristic length \( \delta s \) is the FWHM of the electron density peak. The longitudinal electrostatic field given by the Possion’s equation is: \( E_{\text{static}} = 2\pi n_e c \delta s \). At the head of the pulse where the high density electron piston is forming, the protons, although mobile, provide a uniform background on a short timescale. The estimated peak electron density according to the laser-piston model is plotted in figure 2(a). The effective field due to the ponderomotive force is \( E_{\text{pond}} = -\nabla V_{\text{pond}}/e \), where the ponderomotive potential is given by \( V_{\text{pond}} = \left(\sqrt{1 + |A|^2}/2 - 1\right)mc^2 \). Here \( |A|^2/2 \) is the normalized time-averaged laser intensity profile. In the case of \( |A| \gg 1 \), \( V_{\text{pond}} \approx \sqrt{|A|^2}/2 mc^2 \). For the Gaussian pulse employed in the simulation, we have \( \nabla V_{\text{pond}} = -\left[(1 - 3\pi Z_k^2)/W^2 + \left(Z_k^2/\lambda^2\right)^2\right] A_0 \), where \( \eta = x - ct \) is the relative distance to the pulse center, \( k = 2\pi/\lambda \), \( Z_k = \pi W_0^2/\lambda \) is the Rayleigh length, \( W = W_0 \sqrt{1 + (x/Z_k)^2} \), and \( A_0 = a_0 W_0 \exp\left(-r^2/W_0^2\right) \exp\left(-\eta^2/\left(c\tau\right)^2\right) \). It is well known that the distribution of the ponderomotive force is maximized at \( \eta = c\tau/\sqrt{2} \). If the electron overcomes the barrier at this position, it can propagate through the pulse. This happens when \( \frac{n_e \delta s}{n_i \lambda} \approx \frac{n_i}{2\omega c} \), which is obtained by equating the ponderomotive and the electrostatic force at the foot of the pulse (\( \eta = c\tau/\sqrt{2} \) on the laser axis.)
Due to the density accumulation effect, the electrostatic field overcomes the ponderomotive force. Based on the above estimate, the maximum sustainable electron density is shown in figure 2(a) by dashed blue line. At around \( x = 12.8 \) \( \lambda \), the density described by the piston model exceeds the sustainable limit, which means some electrons will be reflected by the electrostatic field and injected into the laser pulse. In this case, the electron density peak will accordingly decline due to the loss of the reflected electrons, which maintains the balance between the electrostatic and the ponderomotive force. From the maximum electron density evolution in the simulation (green circles) in figure 2(a), one can find the theoretical estimate is close to the simulation result from \( x = 10 \) \( \lambda \) to 12.6 \( \lambda \). After that, the maximum density in the simulation cannot increase and it oscillates around \( 210 \) \( n_c \). The simulation result is well consistent with the analyzed sustainable maximum density. This kind of longitudinal electron injection effect requires a relative high initial plasma density. It is also observed in the case of laser wake-field acceleration \[24\] and the laser-piston ion acceleration \[22\].

The dynamics of the injected electrons is dramatically different in the case with and without QED effects. The NonQED electrons cannot be confined inside the pulse. They are drifting backward, leave the pulse quickly and are eventually trapped by the wakefield as is the case in \[24\]. However, the injected QED electrons can stay in the pulse for a long time and form a modulation structure in the density distribution, i.e. they are trapped by the laser pulse. Trapping means that the relative motion between the laser and the electrons is slow and the electrons spend a long time inside the pulse compared to the NonQED case. In the simulation, half of the electrons (randomly chosen) are identified with QED effects, which radiate photons. The other half are NonQED electrons (with QED module turned off and cannot emit photons). The density distributions are shown in figures 2(b)–(d) in logarithmic scale. At 50 fs in figure 2(b), a typical electron bubble structure is formed and the accumulated electrons are injected into the pulse center. At this moment, the density distributions of the QED electrons (black, top) and NonQED electrons (red, bottom) are almost identical. This is because the number and the momentum of the emitted photons on the head of the laser pulse are relatively small, which do not significantly disturb the electron dynamics. The emission power by a single electron depends on the EM field acting on it. Therefore, when the backward drifting electrons encounter the strong laser field, the difference between the two kinds of electrons becomes clear. In figure 2(c) at 59 fs, the NonQED electrons propagate...
deeper inside the electron bubble than the QED electrons. At 67 fs in figure 2(d), the NonQED electrons have already reached the tail of the bubble. However, the QED electrons just have drifted through half of the bubble only. The QED electrons are distributed in a modulation structure and the separation between each layer is half wavelength. It is due to the oscillating nature of the ponderomotive force of the linear polarization laser pulse, which has an oscillation frequency with $2\omega$. Correspondingly the electron bunches are injected every half laser cycle.

The electron piston structure cannot be maintained for a long distance as the piston filaments and the density significantly decreases [25]. After that, though the maximum head density is still close to the injection threshold, the complete shell structure has disappeared and filaments are formed. Then several electron bunches are injected due to the high local density without forming regular layered structures.

To understand the trapping effect, the simulations are performed where a single electron interacts with the laser field. The initial conditions of the single electron are read from one of the tracing particles in the previous simulation when it is injected into the laser pulse. The electron starts moving backwards at $x = 20\lambda$ with the longitudinal momentum $p_y = -700m_ec$. The laser parameters are exactly same as the previous one. QED and NonQED cases are compared. The electron and photon longitudinal momentum evolution is plotted in figure 3(a). The net effect of the photons emission provides a negative momentum (solid black line). Consequently the backward drift of the electron is reduced due to momentum conservation. This is equivalent to the radiation damping force in the Landau–Lifshitz form

$$F_y \approx -(2\varepsilon^2 / 3m_e^2c^4)v^2([E\cdot v - B/c]^2 - (E - v)\times B/c^2)$$

The longitudinal displacements of the electrons are represented by the colorbar. Before interacting with the laser field at about 35 fs, the motions of the electron in both cases are exactly the same. The QED electron momentum (star line) quickly becomes positive within 5 fs after emitting several photons, which indicates the electron is co-propagating with the laser field with a velocity slightly smaller than the speed of light. The oscillation period of the $p_y$ increases larger and larger, which can be interpreted as the electron has to spend more and more time to penetrate through one laser period. Therefore, the trapped electron drifts slowly inside the laser pulse and will finally leave the laser field. Note that the negative photon momentum shown here indicates the photons emitted by the longitudinal injection electrons are counter-propagating to the laser field. In the NonQED case (cross line), the electron penetrates the laser pulse at the speed of light. In figure 3(b), the profiles of electron density, electron longitudinal momentum, transverse electric field $E_y$ and the longitudinal electric field $E_x$ at $t = 59$ fs along $y = 0$ are displayed (from the main QED simulation with laser-plasma). The modulation structure of the trapped electrons is clearly represented by the $p_x$ profile. The density of the trapped electron bunches is relatively low compared with the density peak in the head.

**Positron bunch production**

The trapped electrons, which are relatively counter-propagating against the laser pulse, generate a large number of photons during the slip process. The photons generated inside the laser pulse are also displayed by their momentum vectors in figures 2(c) and (d) with blue (with positive momentum) and red (with negative...
momentum) arrows. Since these are highly relativistic electrons, the emission direction is correlated to the propagation direction. The photon emissions containing both forward and backward direction representing by the arrows reflect the fact that the trapped electrons are oscillating back and forth with respect to the laser field which is consistent to the longitudinal momentum profiles shown in figures 3(a) and (b). Since the location of these photons are in the region of strong laser field, electron-positron pair creation becomes possible via the Breit–Wheeler process [16, 17]. An important parameter in calculating the probability of this QED process is $\chi_\gamma = (1/E) \sqrt{(\hbar \omega E/mc^2 + k_x \times B/mc^2) - (k_x \cdot E/mc^2)^2}$, here the photon momentum is $k_x = (\hbar \omega - k_c) / mc^2$ [26]. In an EM wave propagating along x direction, $\chi_\gamma = (E/E_c)(\hbar \omega - k_c)/mc^2$, the counter-propagating and co-propagating photons have $\chi_\gamma ^{\pm} \approx 2(\hbar \omega/mc^2)(E/E_c)$ and $\chi_\gamma ^{\mp} \approx 0$, respectively. Therefore the photons with negative momentum, which means they are counter-propagating against the laser, provide a large cross section for the Breit–Wheeler process. In order to check the robustness of the mechanism, a 3D simulation is carried out with the same laser parameters. The simulation box is $35 \times 16 \times 16 \lambda$ with the mesh size 0.02 $\lambda$. Since the particles have more freedom to move in a 3D space, the initial plasma density is increased to 12 $n_c$ to make the head electron accumulation density to overcome the injection threshold in a short distance. The electron and photon density distributions at 80 fs are shown in figure 1. In the head of the electron bubble, the injected electrons have a layer structure as well as in the 2D case. The laser pulse is represented by the green disks and the cross section of the peak transverse electric field is shown in the $y$–$z$ plane. The created positrons are shown by the red spots inside the laser pulse. They follow the same modulated structure as the trapped electrons. The size of the spot is proportional to the energy of the positrons. A positron bunch with more than 2 nano-Coulomb is obtained and the average energy of the positrons is about 1 GeV. The charge and the total energy of the positrons are shown in figures 4(a) and (b) as function of time. The laser-plasma interaction distance is only several microns at this moment. Surely the bunch charge will increase with deeper propagation. The corresponding energy transfer efficiency between laser and the positron bunch is about 0.2%. Based on our simulations, it is found that the regime does not work when the plasma density is too low ($< 10^{-7} n_c$) as the piled-up electron density is not high enough to induce an electrostatic field which could overcome the laser ponderomotive potential. On the other hand, a high density solid target (several tens $n_c$) also does not work well since the laser is reflected after propagating a short distance and the corresponding pair production efficiency will be extremely low. Pair production via Breit–Wheeler process has been widely investigated recently [27–29]. Ribeyre et al [29] proposed a mechanism by the collision of $\gamma$-ray beams and the corresponding pairs have the number of 0.01–0.1 nano-Coulomb. Lobet et al [27] obtained 0.01–1 nano-Coulomb pairs in the collisions of the electron beam and short pulse lasers with different power. Compared with these previous works, the electrons are self-injected into the strong laser pulses in our case and the corresponding setup is simple. The obtained pairs reach the order of 1 nano-Coulomb although it requires a higher laser intensity.

To show the generation of positrons clearly, we run a 2D simulation with large laser spot size (FWHM = 10 $\lambda$). All the other parameters for laser and plasma are the same as the previous ones and the above discussed scenarios repeat themselves. The photon density distribution at 60 fs is shown in figure 5(a). The green curve indicates the laser intensity profile. One finds that the high density region corresponds to the trapped electrons and the photons also have a modulation structure. The energy-angular distribution of the photons at 60 fs is shown in figure 5(b). A large number of backward propagating photons can be found, which contribute to the generation of the positrons and the corresponding $\chi_\gamma ^{\pm}$ reaches 0.75. The momentum spectra of the photons inside the laser pulse are plotted in the inset as time evolves. The number of the forward moving photons are significantly increased. However, the number of the counter-propagating photons are not reduced.
which indicates a consecutive pair creation process can be expected. Figure 5(c) depicts the positron density distribution at 100 fs. A part of the positrons are located in the strong longitudinal electric field. Therefore, both the number and the energy of the positrons are increased as time evolves. The positron bunch is highly collimated with a transverse emittance of 2.8 mm mrad. The energy-angular distribution of the positrons at 100 fs is shown in figure 5(d). The positrons spread in a narrow angle and have ultra-relativistic energy. The charge of the positron beam increases with time and the peak energy is about 1 GeV as seen from the inset. Although the number of the positrons and the creation efficiency is not very high, the positron beam obtained in our mechanism is ultra-short and has ultra-relativistic energy. Several mechanisms have been proposed recently for positron creation and acceleration [30–34]. The positron bunches created in this paper can be used as an ideal external injection source for further acceleration. Such nano-Coulomb positron bunches can be produced with the new generation of 10 PW laser facilities becoming available [3]. We also find that the electron longitudinal trapping and the pair creation are obtained with the circular polarization laser. The reason for choosing a linear polarization laser in this work is that it can be more easily realized in experiments and indeed the 10 PW laser at ELI-Beamlines is designed to have linear polarization.

Conclusions

In conclusion, we propose a longitudinal injection regime for electrons due to the strong electrostatic field generated by high density accumulation. In the ultra intense laser and overdense plasma interaction, this self-injection effect becomes significant. Furthermore, the injected electrons can be trapped in the center of the laser pulse due to the radiation reaction force. In the upcoming laser facilities such as ELI [3], the laser-plasma interaction is ultra-relativistic and radiation dominated. The photons radiated by the trapped electrons counter-propagate in the pulse center which can be an efficient regime for electron-positron pair creation. High energy and well collimated positron bunches are produced. The density of the positrons reaches $10^{21}$ cm$^{-3}$, which can be used as an external injection source for further acceleration.
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