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Numerical studies on pair production in ultra-intense laser interaction with a thin solid-foil

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Abstract

A theoretical and numerical model of photon and electron–positron pair production in strong-field quantum electrodynamics (QED) is described. Two processes are contained in our QED theoretical model, one is photon emission in the interaction of ultra-intense laser with relativistic electron (or positron), and the other is pair production by a gamma-ray photon interacting with the laser field. This model has been included in a PIC/MCC simulation code named BUMBLEBEE 1D, which is used to simulate the laser plasma interaction. Using this code, the evolutions of electron–positron pair and gamma-ray photon production in ultra-intense laser interaction with aluminum foil target are simulated and analyzed. The simulation results revealed that more positrons are moved in the opposite direction to the incident direction of the laser under the charge separation field.

Keywords: QED, ultra-intense laser, gamma ray photon, electron–positron pair

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

1. Introduction

The researches of LPI have been promoted as a result of the development of petawatt or even exawatt laser facilities. These laser facilities include the HERCULES at the university of Michigan which has upgraded to \(10^{22}\) W cm\(^{-2}\) [1], the ELI-NP at European Center [2], APOLLON10 at ILE in France [3], XCELS in Russia, VULCAN10 at RAL in UK [4], especially, the SULF in China [5], all of which are expected to reach the intensities of \(10^{23}–10^{24}\) W cm\(^{-2}\) or even higher. At that time, the corresponding laser field amplitude could reach \(0.3 \times 10^{18}\) V m\(^{-1}\), which is comparable to the Schwinger field (\(1.3 \times 10^{18}\) V m\(^{-1}\)) [6]. As is well known, the Schwinger field can break down the quantum vacuum and produce electron–positron pairs. This intensity level opens the door to the study of the LPI in QED regime [7–12].

The research on pair production is meaningful to positron sources, laboratory astrophysics, radiography for medical applications and so on. In the laboratory, pair production can be realized directly (the trident process) or indirectly (the Bethe–Heitler process) by the interaction of electron and high-Z target material [13, 14]. When the next generation high-power laser reaches the intensity of \(10^{24}\) W cm\(^{-2}\), i.e., the LPI enters the QED field, pair production occurs in the collisions of extreme laser field with the discrete photon. This is called the multi-photon Breit–Wheeler process [15]. Therefore, as one of the QED effects, pair production can not be neglected in the study of strong-field QED effect [16–18].

Since the coupling between the QED process and plasma dynamics in QED-plasma is very complicated, numerical simulations have become essential ways to study the QED effects in recent years. Up to now, there has been a significant interest in the simulations of strong-field QED-plasma using
PIC/MCC method [19, 20]. Several PIC/MCC codes have been developed to contain the QED module, such as EPOCH [21, 22], OSIRIS, SIMLA [23, 24] and KLAPS [25, 26]. However, as far as the authors know, the physical process of the QED effects including the pair production, is not clear yet till now, which requires further simulation research. Thus, in this work, we concentrate on the pair production process rather than the yields in ultra-intense laser and solid interaction.

In this paper, the model of photon and pair production in strong-field QED is presented. And the corresponding modules have been implemented in the in-house LPI simulation code, BUMBLEBEE [27]. Using this code, the evolutions of electron–positron pair and photon production in ultra-intense laser (∼1024 W cm−2) interaction with aluminum (Al) foil target are simulated and analyzed, considering the QED effect. Especially, to explore the process of pair production, we recorded the positions of produced photons and positrons. This article is organized as follows: a brief review of the model and method is presented in section 2, followed by discussions of the simulation results in section 3. The conclusions are summarized in section 4.

2. Theoretical and numerical model of QED

When the laser field is strong enough, electron acceleration caused by laser field could lead to stimulated radiation, which is known as synchrotron emission [28]. This process can be calculated by classical theory. However, if the laser intensity is above 1022 W cm−2 (a ∼ 100, a = eE/maω0) is the dimensionless peak field amplitude. Here, e is the electron charge, E is the electric field amplitude of the laser, me is the electron mass, c is the speed of light in vacuum, ω0 is the laser frequency.), the classical theory will predict that photon energy is higher than electron energy, which is beyond the scope of classical physics. The radiated photons will be further transformed to electron–positron pairs, and even the cascaded phenomenon (photons → pairs → photons → pairs) could happen. Therefore, the quantum correction to the classical physics is essential to calculate the radiation spectrum and total radiation intensity accurately. In this paper, the conversion from photon to pair is considered in the radiation model, i.e., two processes are included in our QED model, one is discrete photon production in the interaction of high-intensity laser with relativistic electron (or positron), and the other is pair production by a gamma-ray photon interacting with the laser field.

The total photon emission frequency in unit time is

\[ v_P(\chi) = \sqrt{3} \alpha_i \eta (2\pi \alpha_c \gamma)^{-1} \int_0^{\eta / 2} F(\eta, \chi_1) / \chi_1 d\chi_1. \]

(1)

Here \( \alpha_i \) is the fine-structure constant \( \alpha_i = q^2 / hc \), q the particle charge, \( h \) is the reduced Planck constant, \( \tau_c \) is the Compton time, \( \gamma \) is the electron relativistic factor, and \( F(\eta, \chi) \) is the quantum correction of radiation spectrum [21].

\[
F(\eta, \chi_1) = \frac{4\chi_1^2}{\eta^2} yK_2/\lambda(y) + \left( 1 - \frac{2\chi_1}{\eta} \right) y \int_t^\infty d\xi K_3/\lambda(t),
\]

(2)

\[ y = \frac{2\chi_1}{3\eta(\eta - 2\chi_1)} \]

(3)

\[ \eta \) is the electron nonlinear quantum parameter,

\[ \eta^2 = \text{coff} \cdot \frac{1}{m_e} \gamma^2 [G^2 + (\vec{q} \cdot \vec{E})^2], \]

(4)

\[ G = q(\vec{E} - \gamma \vec{p} \cdot \vec{E} \vec{p} + c/\gamma \vec{B}), \]

(5)

where \( \text{coff} = 3h/2\alpha m^2 c^4 \). Within each time step \( \Delta t \), the photon emission probability for an electron is \( P_\text{el} = 1 - \exp(-\Delta t \cdot v_P(\eta)) \). Depending on the time step \( \Delta t \) and the external electromagnetic field, \( \Delta v_P(\eta) \) is usually relatively small (<<1) and the photon emission probability is so small that no photons could be emitted within \( \Delta t \). Therefore, \( v_P(\eta) \) is accumulated over the time interval between two emissions until a photon is emitted. And after that, \( P_\text{el} \) is reset to an initial value. The MCC method has been applied to simulate the photon emission process. At the beginning of the simulation, \( P_\text{el} \) is compared with a random number \( R \) sampled from a uniform distribution in [0, 1]. If \( R > P_\text{el} \), no photon emits, and \( v_P(\eta) \) is accumulated till a photon is emitted. If \( R \leq P_\text{el} \), i.e., electron energy has reached the level of emission, a photon is generated in the plasma.

The absorption frequency (or pair emission frequency) of photon with \( \chi_2 \) can be written as

\[ v_p(\chi_2) = \frac{\eta e}{2 \tau_c} \frac{\chi_2}{\chi_3} T_3(\chi_3). \]

(6)

Here, \( \eta \) is the photon energy, \( T \) and \( \chi \) are the parameters which characterize the degree of the pair emission [17]

\[ T_3(\chi_3) \approx 0.16 \left( \frac{K_2^2/\lambda^2/3}{\chi_3} \right) \]

(7)

\[ \chi_3 = \frac{e_p}{\eta} \left[ \frac{1}{2m_e c^2} \frac{[E_p + (c\vec{k}/k) \times \vec{B}]}{E_S} \right], \]

(8)

\[ E_S = 1.3 \times 10^{18} \text{ V m}^{-1} \] is the Schwinger field, \( E_p = E - (\vec{E} \cdot \vec{p})/\vec{B} \) is the unit vector of photon velocity. Similarly, within the time step \( \Delta t \), the pair emission probability for a photon is \( P_\text{ph} = 1 - \exp(-\Delta t \cdot v_P(\eta)). \)

Based on the above theory, the LPI with QED process can be modeled using PIC/MCC method. The simulation flow is shown in figure 1.

From figure 1 we can see that, the entire simulation process mainly contains two parts, the LPI process (marked as PIC in figure 1) and QED process. The LPI process is simulated with the standard PIC method. Three important procedures are contained in the PIC iteration: (1) the field solver, which solves the Maxwell’s equations; (2) the deposit, where the particle charge is accumulated on a grid via interpolation to solve the current density; (3) particle mover, in which the particles are pushed using Newton–Lorentz equations of motion. The QED process is described by MCC method. At first, it should be judged whether the electron (or positron) will emit photon. If yes, a new photon should be injected into the background plasma. Similarly, whether a photon will be converted into electron–positron pair should also be judged. If yes, an electron and a positron should be
For $\varepsilon^-$ or $\varepsilon^+$:
- If emits photon: inject photon
- If absorbed:
  - inject $\varepsilon^-$ and $\varepsilon^+$
  - photon disappears

**QED/MCC**

$\textbf{t} = \textbf{t} + \Delta \textbf{t}$

- Move particles
- Update the current
- Solve Maxwell's Equations

**Figure 1.** PIC/MCC simulation flow of LPI with QED.

![Physical model of QED](image)

**Figure 2.** Physical model of QED.

inserted into the background plasma. Meanwhile, the relevant photon disappears.

### 3. Simulation results and discussion

In our simulation, a p-polarized laser pulse with wavelength $\lambda = 1 \mu m$ is injected onto a thin aluminum foil from the left boundary ($x = 0$) of the simulation box. The laser pulse is $15T$ long and has an intensity of $I\lambda^2 = a^2 \times 1.37 \times 10^{18}$ W cm$^{-2}$ $\mu m^2$, here $T$ is the laser period. We set $a = 540$ (corresponding laser intensity $J \approx 4 \times 10^{23}$ W cm$^{-2}$), which is consistent with [29]. As figure 2 shows, the initial plasma occupies the region from $6\lambda$ to $8\lambda$ (the blue zone), which contains $1\lambda$ density linearly increased district and $1\lambda$ constant district. The electron density within the constant district is $700n_c$ ($n_c = \frac{e_0 m_e \omega_0^2}{\varepsilon^2}$ is the critical density).

In order to observe the process of laser-solid interaction with QED effects, the density profiles of electrons and aluminum ions are presented in figure 3. The position and time are normalized to the laser wavelength $\lambda$ and laser period $T$, respectively, and the density is normalized to the critical density $n_c$.

As seen in figures 3(a) and (b), the variations of electron and ion density are similar. When $t < 6T$, the laser has not reached the plasma region ($6\lambda$, $8\lambda$), and the electron and ion density maintain at their initial states. After $t = 6T$, under the effects of both ponderomotive force and skin depth, the plasma layer is compressed and pushed to the right. The particles will be removed from the simulation once they move out of the simulation region.

To observe the process of pair production, the real-time time–space distributions of the newly-generated photons and positrons are given in figures 4(a) and (b), from which we can get the positions of the first occurrence of newly-generated particles. The color indicates the yields in each moment. Before the laser pulse reaches the plasma ($t < 6T$), there is no photon and positron in the simulation region. After the laser pulse propagates into the plasma, a large number of photons are produced in the region from $6\lambda$ to $8\lambda$. Later, with the laser pulse propagation and plasma layer movement to the right, more photons are generated at a certain frequency. In addition, the density of newly-produced photons is larger than that of electrons and ions. This indicates that photons with higher density than the background plasma are generated, which can be concluded from the comparison between figures 3(a) and 4(a).

In figures 4(c) and (d), the density profile evolutions of total photon and total positron are provided. Compared figure 4(a) with (c), we can find that photons are mainly generated with the plasma propagating to the right, then constantly expand to both sides and spread to the whole space as simulation time increases. Meanwhile, it can be seen from figure 4(b), more positrons are generated as the photons expand to the left. From the density profile of total positron (figure 4(d)), charge separation field is formed as a joint result of the newly-generated positrons and the ions propagating to the right, which makes plenty of positrons move toward the left.

To observe the density distributions of all particles after the laser entered the plasma, the density profiles of four species of particles at $t = 15T$ are shown in figure 5(a). Note that, photons exist in the whole district, which is the same as figure 4(c). Due to the ponderomotive force, electrons and ions ($\text{Al}^{13+}$) only exist on the right side of $x = 8\lambda$. We observe that the positrons are mainly distributed in the region from $6\lambda$ to $8\lambda$, and outside of this region positrons are relatively fewer. This is because electron motion is faster than ion motion, which makes the plasma region show positive electrical property (see figure 5(b)), so positrons will be pushed inversely by space charge force.

To assure the validation of our code, we compare some of the simulation results with EPOCH1D. Under the same conditions, the particle density distributions are similar for the two codes. The values of the photon density and positron density are slightly different, which may come from the different QED theories implemented in the two codes. The $y$-component electric field $E_y$ predicted by the two codes are also compared and agree very well.

### 4. Conclusions

In this paper, the model of photon and pair production in strong-field QED is established using MCC method and implemented into the code BUMBLEBEE 1D. With this code, the interaction of high-intensity laser with high-density
aluminum foil target is simulated. The evolutions of photons, electrons, ions and positrons are observed. Photon and pair production property in the ultra-intense laser-solid interaction, as well as the QED effect in this case, is analyzed. Simulation results revealed that more positrons are produced in the opposite laser direction.

Figure 3. Time–space evolutions of (a) electron density and (b) aluminum ion density. The color bar represents the particle number density.

Figure 4. Particle density: (a) real-time newly-generated photon density, (b) real-time newly-generated positron density, (c) total photon density, (d) total positron density. The color bar represents the particle number density.
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References


Figure 5. Particle number density and charge density distributions with position at $t = 15T$, (a) number density, (b) charge density.