Enhanced electron trapping and $\gamma$ ray emission by ultra-intense laser irradiating a near-critical-density plasma filled gold cone

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Abstract

The radiation trapping effect (RTE) of electrons in the interaction of an ultra-intense laser and a near-critical-density plasma-filled gold cone is numerically investigated by using the particle-in-cell code EPOCH. It is found that, by using the cone, the threshold laser intensity for electron trapping can be significantly decreased. The trapped electrons located behind the laser front and confined near the laser axis oscillate significantly in the transverse direction and emit high-energy $\gamma$ photons in the forward direction. With parameters optimized, a narrow $\gamma$ photon angular distribution and a high-energy conversion efficiency from the laser to the $\gamma$ photons can be obtained. The proposed scheme may offer possibilities to demonstrate the RTE of electrons in experiments at approachable laser intensities and serve as a novel table-top $\gamma$ ray source.

1. Introduction

In the past few years, laser intensities in excess of $10^{22}$ W cm$^{-2}$ have been demonstrated in experiments [1]. By revolutionary advances in laser technology marked by ongoing EU projects such as Extreme Light Infrastructure [2] and proposed initiatives like the International Coherent Amplification Network [3], laser intensity is expected to surpass $10^{25}$ W cm$^{-2}$ in the next 10 years. At such extreme laser intensities, the laser–matter interaction is entering a new unexplored domain [4–6]. For example, a strong electromagnetic field with $E > 10^9$ V m$^{-1}$ will be created so that the laser–plasma interaction becomes highly nonlinear. The exotic near-quantum electrodynamics (QED) regime comes into play, and the classical behavior of particles in laser fields is significantly modified [7–9]. Numerous new phenomena are predicted to appear, e.g., the creation of particles like electrons, muons, pions, and their corresponding antiparticles in vacuum [9, 10]. This opens up new possibilities of studying astrophysics, nuclear and particle physics, high-energy-density physics, etc.

In the near-QED regime, relativistic electrons quivering in an ultra-intense laser field emit strong radiation, which come into being high-energy $\gamma$ photons. Some $\gamma$ photons decay into electron–positron pairs, which can annihilate to produce $\gamma$ photons inversely. During these processes, the radiation field by a charged particle being accelerated or decelerated is sufficiently strong to act back on the particle itself [11]. This is known as radiation reaction (RR), radiation damping, or radiation back-reaction [12–17]. When the radiation damping force becomes significant enough to compensate for the laser ponderomotive force, the laser–plasma interaction experiences a great deal of corrections. This is a highly nonlinear process that has been extensively studied theoretically in past years, though it is very difficult to demonstrate experimentally. Thanks to the advent of super computers, it becomes possible to numerically investigate the relevant processes in detail by large-scale simulations with QED and the RR effect being taken into account in the numerical codes [18–20].

Recently, many contributions have been devoted to this topic. By using the QED-PIC code VLPL, Ji et al investigated the laser–plasma interaction at ultra-high laser intensities and numerically observed the radiation trapping effect (RTE) of electrons in the near-QED regime [20]. It is found that electrons are trapped inside the extreme laser field instead of being scattered off transversely, so that a dense electron beam is finally formed behind the laser front. This is generally thought incredible at low laser intensities, where electrons are usually
pushed away by the laser ponderomotive force. Though the $\gamma$ ray in reference [20] has a high photon energy up to several tens MeV, a dimensionless laser electric field amplitude $a_0 = 500$ (for a laser wavelength 0.8 $\mu$m) is required, which is far beyond the potential outputs of current laser facilities. It is also shown that, once the laser intensity decreases to, e.g., $a_0 = 200$, the trapped electrons become trivial, and the accompanying $\gamma$ ray gets weaker [20]. This poses many challenges in experimental demonstration of the RTE of electrons at current laser conditions.

In this paper, we investigate the RTE of electrons in the interaction of an ultra-intense laser and a near-critical-density (NCD) plasma-filled gold cone by using the particle-in-cell (PIC) code EPOCH [21] with both QED and the RR effect incorporated. It is found that, by using a gold cone, the threshold laser intensity for electron trapping can be significantly decreased. When a laser with $a_0 = 180 \left( I_0 \approx 4.4 \times 10^{22} \text{ W cm}^{-2}\right)$ irradiates an NCD plasma-filled gold cone, a great deal of high-energy electrons are trapped in the cone, forming a dense electron beam with a longitudinal length exceeding 15 $\mu$m and a peak density up to 25 $\times$ 1.12 $\times$ 10$^{21}$ cm$^{-3}$. Meanwhile, these electrons are located behind the laser front and effectively confined near the axis of the laser with a transverse size of only $\sim 3$ $\mu$m. Exposed in such an intense laser field, the trapped electrons oscillate significantly in the transverse direction and emit high-energy $\gamma$ photons in the forward direction. The energy conversion efficiency from the laser to the $\gamma$ photons is up to 10%, which is much higher than those in the so-called betatron radiation cases [12, 13, 22, 23]. This scheme can serve as a novel table-top photon source, and it may benefit the potential experiments for demonstrating the RTE effect at approachable laser intensities in current laboratories.

2. The RR effect and QED in extremely intense laser fields

We start with several critical parameters for the QED and RR effect [6, 7, 10, 17]. With the increase of the laser intensity, electron oscillation created by the radiation damping force becomes comparable with the Lorentz force [7, 17]. Then the electron motion equation is corrected as [11]:

$$\frac{d\vec{p}}{dt} = -e \left( \vec{E} + \vec{\beta} \times \vec{B} \right) + \frac{2e^2}{3c} \gamma \vec{a}_0$$  (1)

Here $e$, $m_e$, $c$ are the electron charge, the rest mass, and the light speed in vacuum, respectively. $\vec{\beta} = \vec{v}/c$ is the normalized electron velocity, and $\vec{E}$ and $\vec{B}$ are the components of the electric and magnetic fields. Here, the first item of equation (1) is referred to as the Lorentz force, and the second item is the radiation damping force with [11]:

$$\vec{a}_0 = \frac{e}{m_e c^2} \left( \frac{\partial}{\partial t} + \vec{v} \cdot \vec{V} \right) \left( \vec{E} + \vec{\beta} \times \vec{B} \right)$$

$$+ \left( \frac{e}{m_e c^2} \right)^2 \varepsilon \left[ \left( \vec{\beta} \cdot \vec{E} \right) \vec{E} + \left( \vec{E} + \vec{\beta} \times \vec{B} \right) \times \vec{B} \right]$$

$$- \left( \frac{e}{m_e c^2} \right)^2 \gamma^2 \varepsilon \beta \left[ \left( \vec{E} + \vec{\beta} \times \vec{B} \right)^2 - (\vec{\beta} \cdot \vec{E})^2 \right]$$  (2)

Equation (2) consists of three terms which take different weights when we calculate the damping force. Considering the fact that the third term is $\gamma^2$ larger than the second one and $\gamma$ times larger than the first one, we ignore the first two terms but keep only the third one when we calculate the damping force, assuming a large electron relativistic factor $\gamma$. Thus the damping force can be rewritten as [20]:

$$\vec{E} = \frac{2e^2}{3c} \gamma \vec{a}_0 \approx - \left( \frac{2e^4}{3m_e c^4} \right) \gamma^2 \varepsilon \beta \left[ \left( \vec{E} + \vec{\beta} \times \vec{B} \right)^2 - (\vec{\beta} \cdot \vec{E})^2 \right]$$  (3)

The energy loss due to the radiation damping becomes larger with the increase of the laser intensity. From equations (1) and (3), we can estimate [7, 17]:

$$\frac{dy}{dt} = -e \omega_0^2 \gamma^2 a_0^2 m_e$$  (4)
Here \( a_0 = eE_0/m_c c_0 \) is the normalized laser electric field amplitude, and \( \omega_0 = 2\pi/\lambda_0 \) is the laser frequency. Integrating equation (4), we obtain the energy loss [17]:

\[
\Delta \gamma = -\frac{2\pi \gamma_0 \alpha_0^2 \omega_0 \tau}{\lambda_0 + 2\pi \gamma_0 \alpha_0^2 \omega_0 \tau},
\]

(5)

Here \( \tau_c = e^2/m_c c^2 \approx 2.8 \times 10^{-15} \) m is the classic electron radius, \( \gamma_0 \) is the electron’s initial relativistic factor, and \( \tau \) is the laser pulse duration. From equation (5), we see that when \( \tau >> \tau_d = \lambda_0/2\pi \gamma_0 \alpha_0^2 \omega_0 \), \( \Delta \gamma/\gamma_0 \approx -1 \) is obtained, which indicates that the radiation loss energy becomes maximal, and the electron motion is significantly modified. This may result in totally different electron dynamics with the case at low laser intensity. Therefore, \( \tau_d \) is a critical parameter for one to evaluate the RR effect. For a laser with a wavelength \( \lambda_0 = 1 \mu m \) and normalized laser electric field amplitude \( a_0 = 200 \), assuming the electron’s initial relativistic factor to be equal to \( \gamma_0 \approx 1000 \), we find \( \tau_d \approx 0.75 \) fs and \( \Delta \gamma/\gamma_0 = -\tau/(\tau_d + \tau) \sim 1 \) if the pulse duration \( \tau > 10 \) fs. Under these conditions, the radiation damping force is of the same order of magnitude as the Lorentz force so that it cannot be ignored anymore.

In the near-QED regime, the QED photon emission generally includes two processes [6]: (1) quantum-corrected synchrotron radiation \( \gamma \) photons \( (\gamma_{\text{photon}}) \) replaced by the nonlinear Compton scattering \( (e^- + n_{\text{laser}} \rightarrow \gamma_{\text{photon}} + e^-) \) [24], where \( n_{\text{laser}} \) is referred to as the laser photon; and (2) multiphoton Breit–Wheeler electron–positron pairs production \( (\gamma_{\text{photon}} + n_{\text{laser}} \rightarrow e^- + e^+) \). In the second QED process, electrons and positrons are accelerated and decelerated in the extreme laser field, and they can annihilate to produce high-energy photons. Thus, we introduce the quantum parameter to characterize the importance of these QED effects, which determines if we have to consider the second QED process or not in the laser–plasma interaction [10]:

\[
\chi = \frac{e^2}{m_e c^4} \frac{\left( \frac{e}{c} \vec{E} + \vec{p} \times \vec{H} \right)^2}{ \left( \vec{p} \cdot \vec{E} \right)^2}.
\]

(6)

Here \( \hbar \) is the Planck’s constant, \( \vec{E} \) and \( \vec{H} \) are the components of the electric and magnetic fields, and \( \vec{p} \) is the electron momentum. When \( \chi < 1 \), the photon emission can be treated classically. For \( \chi > 1 \), the quantum effects dominate, and pair production may occur so that the QED effects such as the electron spin effect and recoil must be taken into account [7, 10]. The peak value of \( \chi \) can be estimated as \( \chi_m = \gamma_0 a_0 \tau_c / (\lambda_0 / \alpha) (2\pi/\alpha) \), where \( \alpha = e^2/\hbar c \) is the fine-structure constant. For a laser with \( \lambda_0 = 1 \mu m \) and \( a_0 = 200 \), and the electron’s initial relativistic factor \( \gamma_0 \sim 1000 \), we have \( \chi_m \approx 0.48 \). In this situation, the nonlinear Compton scattering plays a role and needs to be considered, while the pair production can be ignored. In the following cases, we considered both the RR and QED in the simulations, but the pair production process is ignored and not discussed here. It is because in all following simulations we have \( \chi < 1 \), and the amount of positrons occurring at such laser intensities is very limited [4, 5].

3. EPOCH 2D simulations and results

We employ the QED-PIC code EPOCH [21] with the RR effect and radiation module incorporated to investigate ultra-intense laser–plasma interaction, as schematically shown in figure 1. The simulation box is \( X \times Y = 120\lambda_0 \times 20\lambda_0 \) with a cell size of 0.05\( \lambda_0 \times 0.05\lambda_0 \), where \( \lambda_0 = 1 \mu m \) is the laser wavelength. A gold cone (Au) is located between 5\( \lambda_0 \sim 75\lambda_0 \) in the x-axis with a thickness of 2\( \lambda_0 \). The density of the cone is set as \( n_c = 100n_i \), where \( n_i = m_e a_0^2 / 4\pi e^2 \) is the critical density. The left and right opening radius of the cone are \( R = 7\lambda_0 \) and \( r = 1.5\lambda_0 \), respectively. An NCD hydrogen plasma is filled in the cone, whose initial density is
Each cell is occupied by 48 macro-particles in the region of the plasma. A linearly polarized laser with $\lambda = 1\mu m$ and $\tau = -a r^2$ is incident from the left boundary and focuses on the left opening of the cone, where $\tau = 20\tau_0$ is the full width at half maximal (FWHM), $r_0 = 5\lambda_0$ is the laser focal spot radius, $a_0 = 180$ is the peak laser amplitude, and $T_0 = 3.3$ fs is the laser oscillation period. The electric field of laser is along the $Y$-direction. Absorbing boundary conditions are used for both electromagnetic fields and particles. For reference, the case without using a cone is also simulated to compare with the cone case.

Figure 2 shows the simulation results at $t = 90T_0$. The cases without a cone are discussed firstly to show the RR effect. Figures 2(a) and (c) illuminate the electron density distributions in the $X$-$Y$ plane with and without considering the RR force, respectively. When the RR force is not considered, an obvious channel forms, because the strong ponderomotive force of the ultra-intense laser pulse pushes electrons both radially and forward, as shown in figure 2(c). When the RR force is considered, electrons undergo a backward damping force. Some electrons are kicked back to the laser field behind, as shown in figure 2(a). These trapped electrons oscillate and emit strong radiation. The $\gamma$ photon density distribution with a threshold photon energy 1 MeV is shown in figure 2(e). The electron trapping and related $\gamma$ ray emission are typical QED effects, which have been first reported and discussed in reference [20].

When a gold cone is used, it is noticed that not all electrons are pushed away by the ponderomotive force, as shown in figure 2(d). When the RR force is considered, a great deal of electrons are trapped, as shown in figure 2(b). Generally, the electron trapping depends mainly on the laser intensity, which directly determines the electron energy and the $\gamma$ ray emission intensity. According to the scaling law in reference [20], the minimal laser intensity for effective electron trapping is $a_0 \sim 300$. Since the laser intensity in our simulations is one order of magnitude lower than the threshold intensity ($a_0 = 180$ in the above simulations), only a few electrons are trapped in the w/o-cone case, as seen from figure 2(a). But in the cone case, the electron trapping is greatly enhanced. In figure 2(b), the peak density of trapped electrons is as high as $25n_e$, which is five times larger than the initial electron density. The corresponding electron beam length is $15\lambda_0$ with a transverse size $\sim 3\lambda_0$. Because of the laser focusing in the cone, the trapped electrons are subject to a much stronger transverse laser field and experience more significant oscillation compared with those in the w/o-cone case. The oscillation profile of
electrons in the cone can be clearly seen in figure 2(b). The $\gamma$ photon density distribution with a threshold photon energy 1 MeV is shown in figure 2(f). It can be seen that both the photon density (as high as ${\sim}70n_c$) and the total flux in the cone case are much larger than those in the w/o-cone case. It demonstrates the potential advantages of the cone for enhancing the electron trapping and $\gamma$ ray emission.

In order to clarify the underlying physics of the electron trapping enhancement in the cone case, the density distributions of electrons of the NCD plasma (hydrogen) and of the cone (Au) are diagnosed separately. Figures 3(a) and (c) show the electron density distributions at $t = 90T_0$. It is noticed that, although the electrons of NCD plasma are propelled by the laser ponderomotive force, they are confined by the dense plasma in the cone. As a result, most electrons of NCD plasma are located in the cone, as shown in figure 3(a). Some electrons of the cone enter into the cone as a compensating current, as shown in figure 3(c). Finally, more electrons are decelerated by the RR force and trapped in the cone case.

When the electrons of NCD plasma travel along the cone wall and incite a return current in the cone, a strong self-generated magnetic field $B_z$ is thus produced, as shown in figure 3(d). Here, the laser magnetic field has been cancelled out by averaging the magnetic field per laser cycle. The generation mechanism of $B_z$ has been numerically observed and experimentally demonstrated before [25, 26]. In the w/o-cone case, the trapped electrons also form a current and generate a magnetic field, but the peak value of $B_z$ is only 15% of the laser magnetic field, as shown in figure 3(b). On the contrary, the peak value of $B_z$ becomes close to 40% in the cone case, as shown in figure 3(d). The boosted self-generated magnetic field also plays an important role in electron trapping because it can transversely pinch the electrons, so that the electrons are confined in a smaller zone with a transverse size of only a few laser wavelengths, instead of being scattered off by the intense laser fields. This is very beneficial for the $\gamma$ ray emission.

The trapped electrons are continually accelerated in the laser direction by the laser pressure so that they obtain a high energy up to a few GeV, as shown in figure 4(a). Figure 4(b) shows the $\gamma$ photon energy spectrum, figure 4(c) shows the $\gamma$ photon angular spectrum, and figure 4(d) presents the time evolution of the total photon flux. We use absorbing boundary conditions for both electromagnetic fields and particles (electrons, ions, and photons) so that the particles are not recorded anymore when they flee the simulation zone. For photons, the flux diagnostic is calculated by integrating the photon numbers over the angular. Compared with simulation results in the w/o-cone case, the $\gamma$ photons have a larger cut-off energy and flux, as shown in figures 4(c) and (d). For example, the maximal photon energy in the cone case is up to 1.5 GeV at $t = 90T_0$ when the laser arrives at the cone tip. The total photon flux with an energy above 1 MeV in the cone case is about 1.5 times larger than that in the w/o-cone case. It can be attributed to the larger energy and higher density of the trapped electrons in the cone case. It can be seen from figure 3(d) that the photon flux starts to decrease after $t = 100T_0$. That is because that the laser front has left the right opening of the cone after $t = 100T_0$, and the trapped electrons are no longer increasing. As a result, the $\gamma$ photons do not increase anymore. Meanwhile, part of the high-energy $\gamma$
photons arrive at the simulation boundaries and leave the simulation box. The escaping photons are not recorded anymore in the simulations. Figure 4(c) illuminates the photon divergence. It is seen that the corresponding photon divergence in the cone case is significantly suppressed, which indicates that more photons are emitted in the forward direction. At $t = 130T_0$, the minimal divergence angle in the cone case is only $\sim 7^\circ$, while it becomes $\sim 15^\circ$ when the cone is absent. By roughly estimating, the energy conversion efficiency from the laser to the $\gamma$ photons is nearly $10\%$ in the cone case, while the energy conversion efficiency is only about $5\%$ in the w/o-cone case with the same laser and NCD plasma parameters. This would significantly benefit for its potential application as an efficient table-top $\gamma$ ray source, which may have diverse applications in practice, e.g., generating positrons, Quark, and even anti-protons in vacuum [10].

4. Parametric influences of the target geometry and laser intensity

In this section, we discuss in detail the influences of target and laser parameters on electron trapping and $\gamma$ ray emission. For simplicity, we only take into account three critical factors in the simulations: the size of the right cone opening, the density of the background NCD plasma, and the laser peak intensity.

4.1. The right opening size

First, we discuss the influence of the right opening size. In the simulations, we keep all other parameters unchanged but vary the right opening radius only from $r = 1.5\lambda_0$ to $r = 7\lambda_0$. Figures 5(a)–(d) show the trapped electron density distribution. We find that a smaller right opening is preferable for electron trapping. For example, when we take a $r = 1.5\lambda_0$ cone, a high-density oscillating electron beam with a length up to $28\lambda_0$ and peak density as high as $28n_0$ is trapped in the cone at $t = 100T_0$. By comparison, when we increase the radius to $r = 7\lambda_0$, the peak density of the trapped electrons decreases to $10n_0$. Meanwhile, the length reduces significantly. When the cone becomes a channel, as shown in figure 5(d), only a few electrons are trapped. We attributed it to the different focusing effect of the cone for the laser pulse and the different self-generated magnetic fields generated on the cone wall. On one hand, a laser pulse propagating in a cone with a relatively smaller right opening radius tends to result in a smaller focal spot; on the other hand, the focused laser drives more background electrons travelling along the cone wall and forming a larger return current on the wall so that the
self-generated magnetic field gets boosted. As a result, most background electrons in such a small zone in front of the cone are trapped and pinched in the cone, as shown in figure 5(a). Figures 5(e)–(h) exhibit the corresponding γ photon density distributions at $t = 100T_0$. It can be seen that γ photons with a peak density up to $70n_e$ are obtained in the $r = 1.5\lambda_0$ case, while it becomes $30n_e$ in the $r = 5\lambda_0$ case. When the cone becomes a channel, as shown in figure 5(d), the γ photon flux reduces significantly, which is similar to the w/o-cone case, as shown in figure 2(e). This indicates that the right opening radius of the cone is a flexible parameter for controlling the electron trapping and γ ray emission in future experiments.

Figures 6(a) and (b) present the γ photon angular distributions at $t = 100T_0$ and $140T_0$, respectively. The trapped electrons start to flee from the opening tip and enter into the right vacuum. Many more photons in the smaller right opening case are emitted in the forward direction. Actually, the divergence of the photons is related with the trapped electron divergence, because the photons are emitted in the opposite direction of the electron momentum according to the momentum conservation law [11]. Furthermore, the self-generated magnetic fields in the smaller cone opening case is much larger (not shown here), which helps to pinch the electrons and suppress the divergence of the trapped electrons so that the radiated photons are emitted in a smaller angle and have a better collimation. Figure 6(c) shows the γ photon energy spectrum at $t = 100T_0$. When the right opening radius increases, the γ photon cut-off energy becomes smaller, because both the electron energy and density decrease. A highly collimated high-energy high-density photon beam is preferably obtained when the right

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**Figure 5.** The electron density distributions (left column) and the γ ray density distributions (right column) at $t = 100T_0$ with different right opening sizes: (a), (e) $r = 1.5\lambda_0$, (b), (f) $3.5\lambda_0$, (c), (g) $5\lambda_0$, and (d), (h) $7\lambda_0$. 

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opening radius is small. However, it doesn’t help to increase the photon beam quality by further reducing the right opening radius. Additional simulations have already shown that the trapped electrons would be blocked if the right opening radius is too small. As a result, both the $\gamma$ photon energy and its flux would be suppressed.

Figure 6. The $\gamma$ photon angular distributions at (a) $t = 100T_0$ and (b) $t = 140T_0$. (c) The photon energy spectra with different right opening radii. (d) The total photon flux time evolutions with different right opening radii.

Figure 7. The electron density distributions with different NCD plasma densities at $t = 95T_0$: (a) $n_e = 2n_c$, (b) $n_e = 5n_c$, (c) $n_e = 10n_c$, and (d) $n_e = 15n_c$. 
4.2. The density of NCD plasma

For a fixed laser, the NCD plasma density is closely related with the electron energy ($\gamma_e$) and the laser energy absorption. Here, the NCD plasma is usually referred to as plasma with a density between $n_0$ and $n_1$. In our scheme, NCD plasma is filled in the cone due to its efficient coupling with intense laser pulses [27]. In the following, we investigate the influences of the density of NCD plasma on the electron trapping and $\gamma$ ray emission. Here, four different plasma densities are considered: $2n_e$, $5n_e$, $10n_e$, and $15n_e$. The right opening size is set as $r = 3.5\lambda_0$, and all other parameters are the same as those in figure 2(b). The simulation results are presented in figures 7 and 8.

It can be seen that there exists an optimal NCD plasma density, i.e., $n_e = 5n_e$, for electron trapping. For a higher density plasma, the laser pulse is rapidly exhausted and reflected in the cone, and electrons are piled up in the laser front so that the laser cannot penetrate deeper into the plasma, as shown in figures 7(d) and 8(d). Though more electrons are able to be trapped due to the higher NCD plasma density, the laser pulse gets weaker and shorter when propagating in the cone, so that the trapped electrons are accelerated to a lower energy in the laser propagation direction. In this situation, only a few high-energy electrons located in the laser front contribute to producing high-energy $\gamma$ photons, which has been also observed in the references [28, 29]. By comparison, most low-energy electrons in the cone cannot catch up with the laser field, so that they are left behind, as shown in figures 7(c) and 8(c). Without the laser field, these electrons do not oscillate anymore, and there are no more $\gamma$ photons generated. For a lower density plasma, e.g., $n_e = 2n_e$, the laser pulse can penetrate deeper into the cone without obvious weakening. The electrons trapped in the cone oscillate significantly in the transverse laser fields, as shown in figures 7(a) and 8(a). However, due to the lower density of the NCD plasma in this case, the total numbers of the trapped electrons are also limited.
Figure 8(e) illuminates the angular distributions of $\gamma$ photons for different NCD plasma densities at $t = T_0/130$. When $n_e = 2n_i$, there is a broad angular distribution of $\gamma$ photons. When the NCD plasma density is over $5n_i$, the angular distribution becomes narrow, indicating that most photons are emitted in the forward direction. When $n_e = 15n_i$, the FWHM of the angular distribution is only about 20°. The time evolution of the total photon flux, which is obtained by the integration of the angular distribution, is shown in figure 8(f). At $t = T_0/110$, the total photon number in the $n_e = 5n_i$ case is about 1.6 times larger than that in the $n_e = 2n_i$ case. Further increasing the plasma density, e.g., $n_e = 15n_i$, the total photon flux gets smaller. An obvious photon flux decreasing is observed after $t = T_0/65$ in both the $n_e = 10n_i$ and $n_e = 15n_i$ cases. We attributed the reason of the flux decreasing to the exhaustion of the laser pulse in the cone for a higher density NCD plasma. This further demonstrates our previous explanations on the electron trapping in these cases.

4.3. The laser intensity

Finally, the influence of the laser intensity is investigated. In the following simulations, the right opening size is set as $r = 3.5a_0$, and all other parameters are the same as those in figure 2(b). Figures 9(a)–(d) show the total photon flux evolution at four different laser intensities: $a_0 = 100, 120, 140$, and 160. The corresponding peak quantum parameters $\chi_m$ are: 0.24, 0.29, 0.34, and 0.39, respectively, assuming the electron’s average initial relativistic factor $\gamma \approx 1000$ in our simulations. Therefore, it is reasonable to ignore the pair production process in all cases. As expected, both the $\gamma$ photon density and flux become larger with the increase of the laser intensity. This is because a higher intensity laser is able to penetrate deeper into the cone with a relatively slower decaying rate. Finally, more energetic electrons are generated and trapped in the cone so that a higher photon energy and a larger photon flux are obtained, as shown in figure 9(e). When the cone is used, even though at a very low laser

Figure 9. The $\gamma$ photon distributions in space at different laser intensities: (a) $a_0 = 100$, (b) $a_0 = 120$, (c) $a_0 = 140$, and (d) $a_0 = 160$ at $t = 80T_0$. (e) The photon flux time evolutions at different laser intensities. (f) The photon flux evolution with the laser intensity.
intensity, e.g., $a_0 = 100$, electrons are still able to be trapped, and high-energy photons are emitted. It may be very beneficial for future experimental demonstration, because the required laser intensity for electron trapping and photon emitting is greatly decreased, compared with that in the previous work of reference [20], by using a cone. Figure 9(f) presents the energy conversion efficiency from the laser to the $\gamma$ photons, which is a critical parameter for determining the potential of a scheme serving as a practical $\gamma$ ray source. It is found that, in the $a_0 = 100$ case, the conversion efficiency is about 4.5%. With the increase of the laser intensity, the conversion efficiency becomes larger gradually. Especially, when $a_0 = 160$, the laser conversion efficiency sharply increases to 7.5%. If we increase the laser intensity further, a much higher conversion efficiency is expected. In all our simulations we have $\chi < 1$, so the pair production process can be ignored. If the laser intensity increases continually and $\chi > 1$, nonlinear processes such as the positrons occurring must be taken into consideration, and it is expected that the energy conversion efficiency from the laser to the $\gamma$ photons will be limited.

5. Conclusions

To summarize, using the QED-PIC code EPOCH 2D with the RR effect incorporated, we investigate ultra-intense laser interaction with an NCD plasma-filled gold cone. It is found that, by using the cone, the threshold laser intensity for electron trapping can be significantly decreased. The trapped electrons are located behind the laser front and effectively confined near the axis of the laser field with a small transverse size. Exposed in such an intense laser field, the trapped electrons oscillate significantly in the transverse direction and emit high-energy $\gamma$ photons in the forward direction. We also investigate the parametric influences of the right cone opening size, the NCD plasma density, and the laser intensity. It is found that a smaller right opening size is preferable for electron trapping and $\gamma$ photon emission, the optimal NCD plasma density is around $n_c = 5n_a$, and the energy conversion efficiency increases with the increase of laser intensity. The scheme is expected to be a novel table-top $\gamma$ ray source, which may benefit potential experiments for demonstrating the RR effect at approachable laser intensities in current laboratories.

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