Gamma ray emission via an ultrahigh intensity laser pulse interaction with a laser-wakefield accelerated electron beam

M. A. Bake,1 A. Tursun,1 A. Aimidula,1 and B. S. Xie2

1School of Physics Science and Technology, Xinjiang University, Urumqi 830046, China
2College of Nuclear Science and Technology, Beijing Normal University, Beijing 100875, China

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Abstract

We investigate a method to generation of γ ray photons in collision of an ultrahigh intensity laser pulse with a laser-wakefield accelerated electron beam. We consider the composed target of a homogeneous underdense preplasma in front of an ultrathin solid foil. By using of two dimensional particle-in-cell simulations, we show that the electrons in the underdense plasma are trapped and accelerated by the laser wakefield. When the laser pulse is reflected by the thin solid foil, the wakefield accelerated electron beam continue to move forward and passing through the target almost without the influence of the reflected laser pulse and the foil. Consequently, two groups of γ ray flashes are generated by the wakefield accelerated electron beam interacting with the reflected laser pulse in front of the foil as well as interacting another counter propagating pitawatt laser pulse in the vacuum area behind the foil. The dependence of the emission on the preplasma parameters and driving laser polarization are systematically studied. The use of produced γ rays in future QED research is discussed.

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*Author to whom correspondence should be addressed. Electronic mail: mabake@xju.edu.cn.
I. INTRODUCTION

The idea of laser-wakefield accelerators (LWFAs) are first proposed by the Tajima and Dawson four decades ago [1]. At that time they promise to provide high energy compact electron sources due to its tremendous accelerating gradients which can not be delivered by the conventional radio-frequency (RF) accelerators. In RF the metal cavity have electric break down limit, they cannot support electric field gradients greater than 100 MV/m. This requires very long acceleration length for achieve a GeV scale electron beam. However, the plasma have not the electric break down limit and can support more than 100 MV/m, even 100GV/m acceleration gradients [2].

In the LWFAs, an ultra-short intense laser pulse interacts with plasma can induce an electromagnetic wave in its wake, the plasma electrons can be trapped and accelerated by this wakefield to high energies over centimeters [1, 3]. Since the forty years, a large amount of investigations are carried out to enhance the LWFAs qualities [4, 5], namely get to energetic electrons with small energy spread and emittance [6, 7], which have potential applications in many new developed researches. Recent related researches indicate that the electron beams with energies of several GeV could be obtained by LWFAs [8–10]. Such an energetic electrons will be provided novel compact light sources under the ultrahigh intensity laser conditions [11–13], which also have some applications in the medicine, biology, industry, condensed matter, high energy density science and so on [14].

With the rapid advancement of the ultrahigh intensity laser technologies and related experimental conditions, some new developed Petawatt (PW) laser facilities could deliver ultrashort laser pulses with the intensities up to $10^{23} - 10^{24}$W/cm² [15–18]. One of the most important applications of such an intense laser pulses are the generation of bright $\gamma$ rays thorough QED processes in the laser plasma or laser electron beam interactions [19–22]. Because of their potential applications in many fundamental researches, the considerable efforts has been made to investigate the laser-driven compact $\gamma$ ray sources. Some recent theoretical and experimental research results reveal that bright and energetic $\gamma$ ray flashes and electron-positron pairs can be generated in ultrahigh intensity laser-plasma interactions [23–27]. Therefore, various schemes to get compact, tunable, flexible and bright $\gamma$ ray sources are under investigation and give some explanations of the unlaying physical processes. The most extensively studied laser-based $\gamma$ ray sources scheme are the laser-driven bremsstrahlung emission [28], synchrotron-like radiation [29], and all-optical $\gamma$ ray source [30]. However, the resulting $\gamma$ rays by these mechanisms has the same shortcoming of
broad energy divergence, low energy conversion efficiency, low $\gamma$ ray yields and low final energy, which results some limit to its practical applications.

In order to reach the goal of making compact $\gamma$ ray source, some researchers continued their studies and many kinds of methods have been suggested on synchrotron-like radiation and all-optical $\gamma$ ray source. Because these schemes are still highly promising candidates to compact $\gamma$ ray sources based on currently available laser systems. Among them Ta Phuoc et al. first studied the all-optical Compton gamma-ray source [30]. They predicted the possibility of high energy $\gamma$ rays through the simple Compton backscattering in a laser-plasma accelerator. Chen et al. experimentally investigated the method of $\gamma$ ray generation from inverse Compton scattering laser wakefield accelerated electrons [23]. Recently, Yan et al. studied the nonlinear regime of Thomson scattering in the laboratory by using intense laser interacting with laser wakefield accelerated electrons [23]. Lobet et al. studied the pair production process in the collision of a laser-accelerated electron with a multipetawatt lasers [25]. Most recently Liu et al. discussed an efficient method to generate $\gamma$-rays/hard X-rays by using double-layer target and all-optical process [32]. One of the our recent study [22] also indicated that electron beams with energy of 500MeV to 1GeV, which can be obtained by current LWFA's, interacting with ultrahigh intensity laser can produce high energy photons and positrons. All of these studies mentioned above as well as many other researches [33–35] are theoretically, numerically and experimentally predicted that LWFA's might be abundant sources of the $\gamma$ rays and positrons in the laboratory. This will motivate much efforts on the related researches and improve our understanding the QED processes of $\gamma$-ray emission, pair production and QED cascades.

In this paper, we numerically investigate the $\gamma$ ray emission in the strong laser interaction with gas-foil compound target by using PIC simulations. In our method energetic electrons can be produced in bubble during an intense laser propagating in the underdense preplasma. Then the driving laser pulse can be reflated by the solid foil, which placed behind the preplasma, and interacting with the laser wakefield accelerated electron beam. As the same time, the electron beam can passing through the foil and collide with another counter propagating high intensity laser pulse. As a result, the $\gamma$ rays are produced at the front and back side of the solid foil. We will study the influences of the laser polarization and preplasma densities on $\gamma$ ray emission.
FIG. 1: (Color online) The schematic diagram of our proposed scheme to the γ ray production process by using composed target of a homogeneous low-density preplasma in front of an ultrathin solid density foil. (a) An intense laser interacting with underdense preplasma and energetic electrons are generated in bubble (the LWFA process). (b) The laser are reflected by the solid foil and interacted with the forward LWFA electron beam in the bubble. (c) The electron beam pass inertially through the foil with little energy loss and collide with another counter propagating high intensity laser pulse. The preplasma density are \( n = 0.05n_c \) and \( n = 0.01n_c \) in our different simulations while the foil density fixed to \( n = 20n_c \).

II. LASER WAKEFIELD ELECTRON ACCELERATION

We will investigate the γ ray emission by a wakefield accelerated electron beam interacting with strong laser pulse in this paper. And it well known that the LWFA is the best way to get such a high energy electron beams in laser plasma interaction. In a first stage, we give the basic formalism which have been studied by many research groups since the LWFA scheme was proposed. The relativistic motion of an electron, with mass \( m \) and charge \( e \), in the laser field can be given by the Hamiltonian as \[3, 4\]:

\[
H = \sqrt{m^2c^4 + c^2p_{\parallel}^2 + (c p_{\perp} + e A_{\perp})^2 - e \phi},
\] (1)

where \( p_{\parallel} \) and \( p_{\perp} \) are the longitudinal and transverse components of the electron generalized momentum, \( A_{\perp} \) is the vector potential of the laser electric field, \( \phi \) is the wakefield potential, \( c \) is light speed in vacuum. For convenience we assume that the ion motion is negligible for fast process, and the involved physical quantities are normalized. In the introduced longitudinal moving frame \( \xi = x - v_g t \) with the group velocity \( v_g \) which equals to the wake moving velocity, we can rewrite
FIG. 2: (Color online) Spatial distribution of the electron densities in the \((x,y)\) plane at \(t = 225\) fs (a), \(t = 337\) fs (c), \(t = 420\) fs (e), respectively. And electrons phase space portrait \((x,p_x)\) \(t = 225\) fs (b), \(t = 337\) fs (d), \(t = 420\) fs (f), respectively. The preplasma and foil density are \(0.05n_c\), and a circularly polarized laser pulse with \(a = 20\) is used in this simulation.

The Hamiltonian as

\[
h = \sqrt{1 + p_x^2 + a^2} - \varphi - \beta_{ph} p_x = h_0, \tag{2}
\]

where \(a = eA/mc^2\) is the normalized laser electric field amplitude, \(\beta_{ph} = v_g/c\) is the wakefield phase speed, and \(h_0\) is the integral constant depends on the initial conditions. For the cold plasma electrons the initial transverse momentum of the electron can be neglected, then \(h_0 = \sqrt{1 + p_{x0}^2} - \beta_{ph} p_{x0}\), were \(p_{x0}\) is electron initial longitudinal momentum. Then Eq. 2 gives the electron longitudinal momentum as

\[
p_x = \frac{\beta_{ph}(\varphi + h_0) \pm \sqrt{(\varphi + h_0)^2 - (1 - \beta_{ph}^2)(1 + a^2)}}{1 - \beta_{ph}^2}. \tag{3}
\]

The electrostatic wakefield potential in the electron plasma is given by the Poissons equation

\[
\frac{\partial^2 \varphi}{\partial \xi^2} = k_p^2 \gamma_p^2 \beta_{ph}^2 \left[ \frac{\gamma_{ph}(1 + \varphi)}{\sqrt{\gamma_{ph}^2(1 + \varphi)^2 - (1 - \alpha^2)^2}} - 1 \right], \tag{4}
\]
where $\gamma_{ph} = 1/\sqrt{1-\beta_{ph}^2}$ is the relativistic factor. We shall consider Gaussian laser pulse and profile, related laser parameters will be given in the next section.

III. PIC SIMULATION MODEL

In order to demonstrate our scheme, we carried out a set of two-dimensional (2D) QED-PIC simulations using the code EPOCH [36]. In simulations, we consider a composed target of a homogeneous low-density preplasma in front of an ultrathin solid foil, as showed in Fig. 1. The preplasma is located from $x = 10\mu m$ to $x = 70\mu m$ in $x$ direction and from $y = -25\mu m$ to $y = 25\mu m$ in $y$ direction. The thickness of the solid foil is $1\mu m$. We consider two kinds of preplasma density with $n = 0.05n_c$ and $n = 0.01n_c$ while the foil density fixed to $n = 20n_c$, where $n$ is the electron density and $n_c = m\omega^2/4\pi e^2$ is the critical density corresponding to the incident laser pulse, $\omega$ is the laser frequency.

For the LWFA the linear/circular polarized Gaussian laser pulse (driving laser pulse) are used with wavelength $\lambda = 1\mu m$, spot size $y_0 = 6\mu m$, and the normalized amplitude is $a = 20$. The another counter propagating laser pulse (colliding laser pulse) has a normalized amplitude of $a = 500$ while other parameters are same as driving laser pulse. In simulation, two laser pulses enter the simulation box from the left (driving pulse) and right (colliding pulse) boundaries at $t = 0$ simultaneously, and propagate along the positive and negative $x$ direction respectively.

Some other simulation parameters are chosen as the following: the width and height of the simulation box are $120\mu m$ and $50\mu m$ respectively, which corresponding $3600\times1000$ grid cells. 20 macro electrons for preplasma and 50 macro electrons for solid foil are setting in each grid cell. In our simulations, we assume that the ions motion is negligible and electron initial temperatures are small that their effects can be ignored. The periodic and simple-outflow boundary conditions in transverse and longitudinal directions are used in the simulations.

IV. PIC SIMULATION RESULTS AND DISCUSSIONS

First we show our simulation results of the wakefield electron acceleration process. Figure 2 (a) shows the distribution of the preplasma electron density at $t = 225$ fs for $n_e = 0.05n_c$. The results indicate that the preplasma electrons are pondermotive pushed away from the laser focal areas and plasma bubble is developed. Consequently, some electrons are trapped and accelerated.
FIG. 3: (Color online) The energy spectrum of the electrons at $t = 225$ fs (blue curve), $t = 337$ fs (red curve), and $t = 420$ fs (yellow curve), respectively; the blue curve represents to initial electron spectrum accelerated by wakefield, red curve represents to the spectrum after the accelerated electron beam interacting with reflected laser pulse, and the yellow one represents to the spectrum after electron beam scattering by colliding laser pulse behind the foil. The other parameters are the same as in Fig. 1 and Fig. 2.

by this bubble field. From the phase space distribution of the electrons, in Fig. 2 (b), we can observe two groups of accelerated electrons. One group by ponderomotive accelerated electrons in front of the laser pulse (the right pick ) while another one is the wakefield accelerated electrons (the left pick). These results show that an electron beam with electron density about $n_e = 3n_c$ and momentum about $p_x = 2000$ is created by the LWFA process.

The Fig. 2 (c) and 2 (d) shows the distribution of the preplasma electrons and corresponding phase space portrait at $t = 337$ fs, respectively. It is indicated that, after the laser pulse reflected by the solid foil and interacting with electron beam, the electron beam is still traveled along the positive $x$ direction with less influence of the reflected laser, passing through the solid foil and enter the back vacuum area with beam radius of about $r_e = 2\mu m$ and density of $n_e = 0.4n_c$. We can see that as the laser pulse reflected from the foil, bubble structure are destroyed, this results the electron beam escape from deceleration phase easily. Consistently, the wakefield accelerated electron beam can going through the foil with narrow emittance and almost the same momentum as in bubble, as shown in Fig 2 (c) and 2 (d). It is found that monoenergetic electrons accelerated by the bubble electric field is neither affected by the reflected laser pulse nor by the solid foil. As a result, they appear at the back of the foil as a narrow energetic electron bunch.
Figure 2(e) and (f) are presented the simulation results of another counter propagating high-intensity laser pulse interacting with the electron beam behind the foil at $t = 420$ fs. One can be found that very thin electron sheet, with density of $n_e = 0.5n_c$ and height about $9\mu m$, are appeared. The phase-space portrait of longitudinal component of the electron beam momentum are plotted in Fig. 2(f). It shows that the electron beam momentum is negative. These results generally can be attributed to the fact that, during the electron beam collide with the counter propagating laser pulse, electrons decelerated and stopped by the laser, change its direction to negative $x$ direction and accelerated by colliding laser pulse again. Note that, in our simulations the colliding time is choose as the electron beam colliding with laser pulse before it expands by Coulomb repulsion in order to enhance the efficiency of $\gamma$ ray emission. We can also be seen from Fig. 2(e) that a bubble structure is developed by reflected laser pulse and moving to negative $x$ direction but we have not discuss it.

Figure 3 is plotted the energy spectra of electron beam at different times, i.e. the electrons still in the bubble ($t=225$fs), the head of electron beam going through the foil after interacting with reflected pulse ($t=337$fs), and after the electron beam scattering with colliding pulse behind the foil ($t=420$fs), with same laser and plasma parameters. We can see that an electron beam with maximum energy more than 200 MeV are created by LWFA mechanism and it keeps a good shape (see Fig. 2(c)) and maximum energy when it appears behind the foil. This also indicate that the electron beam almost unaffected by the reflected laser pulse and the foil during go through behind the target. This results the pure process of electron beam and laser pulse interaction, which has some potential applications in study of the strong laser and electron-beam interactions. It is worth to noted that, during the reflected laser pulse interacting with the electron beam, the electrons are decelerated by the laser and emit $\gamma$ ray photons through inverse Compton scattering, this resulting in a decrease in maximal energy of electrons some extent as time goes on as shown the inset in Fig. 3.

Now, we consider the properties of the wakefield accelerated electron beam and laser interaction process in more detail. Figure 4 displays the spatial distributions of the $\gamma$ ray photons density in the $(x,y)$ plane at different times. We can see from the Fig. 4(a) that $\gamma$ ray photons can also produced during bubble formation by Betatron oscillation of the electrons in the bubble. However, it has large space distribution characteristics and the maximum energy is only about 1 MeV as shows in Fig. 5(a). One can clearly see from Fig. 4(b) that a long $\gamma$ ray can be produced in the bubble by wakefield accelearated electrons interacting with reflected laser pulse, and its maximum
FIG. 4: (Color online) Spatial distribution of the photon densities in the \((x, y)\) plane; (a) before the electron beam collides neither with reflected laser pulse nor with colliding laser pulse at \(t = 225\) fs, (b) after the electron beam interacting with reflected laser pulse in front of the foil at \(t = 337\) fs, and (c) after the electron beam scattering with colliding laser pulse behind the foil at \(t = 420\) fs. Other parameters are the same as in Fig. 1 and Fig. 2.

Energy reaches to above 20 MeV with photon number more than \(10^{10}\) as shown in Fig. 5(a). Figure 4(c) shows that a very short \(\gamma\) ray can be produced by the electron beam interacting with a counter propagating high intensity laser pulse behind the foil. This result shows that the \(\gamma\) ray maximum energy is exceed 400 MeV and number of the emitted photons are still above \(10^{10}\) as shows in Fig. 5(a). During the wakefield accelerated electron beam interacting with the reflected laser pulse in the bubble, because of the electron beam itself is long and the reflected laser cannot compress the electron beam, the reflected laser pulse acts like an undulator. This results a long \(\gamma\) ray flash in space. However, for the interaction of the electron beam and counter propagating high intensity laser pulse behind the foil, the laser field is very intense and the all of the electrons are stopped and reflected by the strong laser field and compressed in a small space. Consequently, a very short \(\gamma\) rays with high energies are produced in the interaction.

Figure 5(a) depicts the energy spectrum of the \(\gamma\) ray photons before and after the electron beam interacting with reflected laser pulse in the bubble and colliding laser pulse behind the foil. We
FIG. 5: (Color online) (a) The energy spectrum of γ ray photons at at $t = 225$ fs (blue line), $t = 337$ fs (red line), and $t = 420$ fs (yellow line), respectively. (b) The evolution of the number of γ ray photons with time. Other parameters are the same as in Fig. 1 and Fig. 2.

can clearly see that the photons energy increases factor of 10 after the electron beam interacting with reflected laser pulse. And maximum photon energy up to 500 MeV after the collision of the electron beam with a counter propagating laser pulse behind the foil. Figure 5(b) shows that the evolution of the number of γ ray photons with time. During the LWFA process there are few low energy photons by electron betatron oscillation in the bubble field. When the electron beam interacting with the reflected laser pulse, a copious of photons are emitted, the total yield of photons is reached about $3 \times 10^{16}$ and keeps it as a while. After the electron beam are going thorough behind the foil and scattered by colliding laser pulse, the total yield of photon reaches $5 \times 10^{16}$ at time $t = 420$ fs.

Finally, we investigate the effects of the wakefield driving laser polarization and preplasma parameters on the efficiency of γ ray emission. In our simulations we consider linearly and circularly polarized laser pulses and two kinds of preplasma with density of $n = 0.01n_c$ and $n = 0.05n_c$ while the foil density is fixed to $n = 20n_c$. Figure 6(a) depicts the the angular distribution of the γ ray photons at time $t = 420$ fs. One can clearly see that more γ ray photons could be generated in the circularly polarized laser cases when the preplasma density are chosen as $n = 0.05n_c$. In this case, the HWFM of divergence angle is about 20° and corresponding total photon number about $10^{14}$. 
FIG. 6: (Color online) (a) The angular distribution of the $\gamma$ ray photons after electron beam scattering with a colliding laser pulse behind the foil at time $t = 420$ fs for different laser polarization and different preplasma densities of $n = 0.01n_c$ and $n = 0.05n_c$. (b) The corresponding energy spectrum of $\gamma$ photons at time $t = 420$ fs. (c) The evolution the number of the $\gamma$ ray photons with time for different laser polarization and different preplasma densities of $n = 0.01n_c$ and $n = 0.05n_c$.

Figure 6(b) and (c) present the energy spectrum and the evolution the number of the $\gamma$ ray photons with time $t$, respectively. The results also indicate that for slightly higher preplasma density the circular polarized laser pulse has the great advantages to generate more $\gamma$ ray photons with smaller divergence angle. It is because, for the higher preplasma density greater bubble field can be build and more electrons can be trapped and accelerated by this field. Besides, the circular polarized laser pulse could effectively suppress the electrons transverse oscillation and heating, then more electrons concentrate at the bubble center. Consequently, the more energetic electrons can escape from the deceleration field in the bubble front and sheath electric field rear the foil more easily. Then, more electron collide with an counter propagating laser pulse and emit more $\gamma$ ray photons compared with lower density preplasma and linearly polarized laser case.
V. CONCLUSIONS

In this paper, we have studied an efficient method to generation of the $\gamma$ ray photons by the interaction a wakefield accelerated electron beam with an counter propagating high-intensity laser pulse. In our simulations we used the compound plasma target with an underdense preplasma and a solid foil attached to the preplasma. We have considered the different preplasma densities while the foil density is unchanged. The circularly and linearly polarized laser pulses are used in our studies to induce the wakefield. Our numerical simulations are performed by using the QED-PIC simulation code EPOCH, which includes the processes of synchrotron photon emission and electron-positron pair creation using the Monte Carlo model. The simulation results show that a bubble structure can be developed by the interaction of an intense short circularly/linearly laser pulses with the preplasma. Consequently, the electrons trapped and accelerated in the bubble to high energies. As the laser pulse reflected by the solid foil, the bubble structure is destroyed and the accelerated electrons can passing behind the foil and keeps its shape, number and energy very well. It is found that the energetic electrons appear at the back of the foil as a energetic electron beam with little energy loss and divergence.

The 2D QED-PIC simulation results are indicated that two groups of $\gamma$ rays are produced in this method. During the interaction between the wakefield accelerated electrons and reflected laser pulse from the foil, a long $\gamma$ ray is produced in bubble. As the time goes on a short $\gamma$ ray, with the divergence angle about $20^\circ$ and photon number about $10^{14}$, are produced by the interaction of an counter propagating high-intensity laser pulse with the forward traveling electron beam behind the foil. It is also found that, in this method the, $\gamma$ ray emission are closely related to the wakefield driving laser polarization and preplasma density. We found that slightly higher preplasma density and circular polarized laser pulse has the great advantages to generate more $\gamma$ ray photons with smaller divergence angle. Namely, $\gamma$ ray maximum energy, number and energy spread are greatly enhanced when the preplasma parameters and laser polarization are chosen properly.

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