



Article Simulation Study of a Bright Attosecond γ -ray Source Generation by Irradiating an Intense Laser on a Cone Target

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Abstract: The interaction between an ultrastrong laser and a cone-like target is an efficient approach to generate high-power radiations such as attosecond pulses and terahertz waves. The objective is to study the γ -ray generation under this configuration with the help of 2D particle-in-cell simulations. It is deciphered that electrons experience three stages, including injection, acceleration and scattering, to emit high-energy photons via nonlinear Compton scattering (NCS). These spatial-separated attosecond γ -ray pulses own high peak brilliance (>10²² photons/(s·mm²·mrad²·0.1%BW)) and high energy (6 MeV) under the case of normalized laser intensity $a_0 = 30$ (I = 2 × 10²¹ W/cm²). In addition, the cone target turns out to be an order of magnitude more efficient in energy transfer compared to a planar one.

Keywords: laser-plasma interaction; γ -ray generation; particle-in-cell (PIC) simulation

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1. Introduction

The invention of chirped pulse amplification (CPA) [1] technology has launched an upsurge of physical research by utilizing the laser-plasma interaction, such as fast ignition nuclear fusion [2], the generation and acceleration of high-energy electrons and ions [3,4], high-order harmonic generation (HHG) and the generation of an attosecond pulse [5–7]. In particular, the HHG is an effective mechanism to break the femtosecond time limit and obtain an attosecond pulse, which is widely used in the field of ultra-short x/γ -ray radiation source generation [8]. Attosecond pulses have been widely applied in many fields since their discovery, such as attosecond pump-probe [9], electronic correlation [10] and charge migration in biomolecules [11]. In addition, the γ -ray source based on laser– plasma interactions is different from the traditional accelerator radiation source: it has the advantages of a high brightness and compact construction, and has important application prospects in basic scientific research, medical treatment, industry and some other fields [12,13]. The interaction of a relativistic high-intensity laser with a solid target is considered as a promising method [14] to improve the intensity of attosecond light sources, including the mechanisms of the coherent wake emission [15], the relativistic oscillatory mirror model (ROM) [16] and the coherent synchrotron emission (CSE) [17].

Studying the laser-induced light sources is a task performed to deal with the electron motions, and recent studies have shown the benefits of using a cone target to generate electron beams and radiations [18,19]. Due to the focusing effect of the cone target on the laser, the electron density obtained at the tip of the cone target is ten times higher than that of the planar target [18]. Wang et al. [20] pointed out the benefits of generating



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Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). intense attosecond pulses carrying orbital angular momentum by irradiating a cone target with a circularly polarized laser, which results in an electric-field component normal to an off-axis laser field obliquely incident, and relativistic surface oscillations convert the laser pulses to harmonic radiation via the ROM mechanism. Furthermore, a recent study has shown that the cone target structure can be employed to generate terahertz pulses efficiently because using the cone target improves the hot electrons' conversion efficiency and the energy of the electrons, both of which contribute to a stronger terahertz source with better collimation [21].

However, the γ -ray generated from a cone-like target has not been systematically studied yet, and it promises to be a highly efficient γ -ray source. In this work, we propose an all-optical scheme in which a linearly polarized laser irradiates a cone target to generate attosecond pulses when the laser reaches the sides of the cone target, similar to the laser irradiating obliquely on the planar target. By comparing 2D-PIC simulations of the cone's different open angles, we found that the laser-to-photon energy conversion efficiency is the highest at 90°, the cut-off energy of the γ -ray obtained reaches 6 MeV, the FWHM (full width at half maximum) of a single pulse can reach 267as and the peak brilliance can reach >10²² photons/(s·mm²·mrad²·0.1%BW). In addition, the simulation comparison between the 90° cone target and a planar target shows that the laser-to-photon energy conversion efficiency under a cone target is 12 times that of a planar target and is an order of magnitude higher than that in ref. [22].

2. Simulation Setup

The configuration of this setup is shown in Figure 1: when a linearly polarized laser irradiates a 90° cone target along the angular bisector of the cone, the laser is polarized along the +y direction (*p*-polarized) and propagates along the +x direction. The open-source, high-performance and multi-purpose particle-in-cell (PIC) code for plasma simulation Smilei [23] was used to carry out the 2D-PIC simulations.



Figure 1. (Color online). The schematic diagram of an ultra-intense laser pulse irradiating a carbon cone target.

The laser field set on the left boundary is $a = a_0 \exp(-(t - t_0)^2/\tau^2) \exp(-y^2/w^2)$ $\sin(\omega_0 t + \phi)$, where $a_0 = eE_0/m_e\omega_0 c = 30$ is the normalized amplitude of laser field, $2\tau = 3T_0$ is the pulse duration of the laser and $w = w_0\sqrt{(1 + (x_s/f)^2)}$. $w_0 = 5\lambda_0$ is the focal spot radius, $x_s = 8\lambda_0$, and $f = \pi w_0^2/\lambda_0$ is the Rayleigh length, $\lambda_0 = 800$ nm. $a_0 = 30$ corresponds to the laser peak intensity of I $\approx 2 \times 10^{21}$ W/cm², which is approximately two orders of magnitude lower than the maximum laser intensity currently available [24]. The grid size of the simulation box is $16\lambda_0 \times 24\lambda_0$ with 4096 × 6144 cells. The numbers of macroparticles of electrons and ions for each cell are both 16. The cone target's longitudinal and lateral length are set as $12\lambda_0$ and $24\lambda_0$, respectively, and the angular bisector of the cone target is positioned at $y = 12\lambda_0$.

The thickness of the cone target is $d = 0.3\lambda_0$ and the density is $n_e = 40n_c$, where $n_c = m_e \epsilon_0 \omega_0^2 / e^2 \approx 1.72 \times 10^{21} \text{ cm}^{-3}$ is the critical density of plasma when the laser wavelength $\lambda_0 = 800 \text{ nm}$. The preplasma with a scaling length $L = 0.12\lambda_0$ is also considered in the cone's inner side, whose density increases exponentially from n_c to $n_e = 40n_c$, which corresponds to the similarity parameter [25] $S \equiv \frac{n_e}{a_0 n_c} \approx 1.33$. It ensures that the target is opaque to the laser and also allows the laser to oscillate on the target surface, such that this setup is in favor of HHG.

3. Results and Discussion

3.1. Electrons Injection and Acceleration

Plasma mirrors have been proven as fantastic electron injectors for vacuum laser accelerations [26,27]. However, as the electrons propagate with the reflected laser, the electron slice is defocused and its density decreases rapidly. Therefore, a cone-like target may localize the electrons' motions and act as a brilliant light source by utilizing the dense electron pulses. As shown in Figure 2a, when the incident laser irradiates on the inner side of the target, the reflected part E_x gathers into the center area and gets superimposed with the part E_y that still propagates forward. Additionally, under the action of the laser's ponderomotive force, Lorentz force and the ions' electrostatic force, quite a large amount of the electrons can be observed to escape out of the inner side after the reflection of the electromagnetic field and then constitute dense electron pulses traveling with the reflected field. If we define the electromagnetic field perpendicular to the target's inner side, it can be written as

$$E_{\perp} = E_x \cos \alpha + E_y \sin \alpha \qquad (y > 12\lambda_0), E_{\perp} = E_x \cos \alpha - E_y \sin \alpha \qquad (y < 12\lambda_0),$$
(1)

where $\alpha = 45^{\circ}$ is half of the open angle. It is comprehensible that, when $E_{\perp} > 0$, the electrons are pulled out of the target, and when $E_{\perp} < 0$, the electrons are pushed into the target. Since E_x and E_y are both periodic functions about T_0 , E_{\perp} periodically reaches its largest point and the electron pulses separated by T_0 are formed outside the surface. Regarding the ponderomotive force, whose period is $T_0/2$, it only provides the electrons with relatively rapid oscillations. Therefore, the electron pulses appear synchronously with the peaks of E_{\perp} (Figure 2a). Furthermore, due to the similarity parameter $S = n_e/n_c a_0$ being 1.3, this setup is in favor of high harmonic generations (HHG). Therefore, the reflected field E_x appears as attosecond pulse trains, whose spectrum is consistent with the power-law under the mechanism of a relativistic oscillation mirror (Figure 2b), i.e., $I \propto (\omega/\omega_0)^{-8/3}$, and we can know that the peaks in E_{\perp} originate from the reflected attosecond pulses.

Particle tracking is carried out to further understand the emission of HHG and electron escaping and subsequent motions. An effective process begins with the electron acceleration from the interior of the target towards the surface (Figure 3a). Due to the decrease in the ponderomotive force, the compressed electron bunches are mainly under the action of the charge separation field, which accelerates the electrons to tens of MeV. After a transverse acceleration induced by the incident laser, electrons experience an attosecond pulse emission along with an energy decrease. Typical electron trajectories are illustrated in Figure 3a to demonstrate this emission process, after which, part of them fall back to the target because of energy loss, whereas the others achieve second accelerations to escape from the target.

Figure 3b–d demonstrates the electron's behavior after leaving the target surface. Before reaching the position labeled as time t_1 , the electron energy decreases due to the negative work carried out by the y-direction electric field, which is superimposed by the electrostatic field and the incident laser's electric field. After the direction change in the laser's electric field, the electron energy gets restored to a certain extent until the time t_2 . This is exactly the second acceleration that we called, and this process is an account for the electron's escaping, which has not been specifically investigated before.



Figure 2. (Color online). (a) The distributions of the electric field perpendicular to the target E_{\perp} (normalized to E_0) and electron density n_e (normalized to n_c) at $t = 15T_0$. The mini figure on the right shows the distributions of E_{\perp} and n_e at $x = 8.75\lambda_0$ (the black dotted line), in which, the yellow dotted line represents E_{\perp} and the blue dotted line represents n_e . There are three electron bunches near $y = 10\lambda_0$, $y = 11\lambda_0$ and $y = 13.6\lambda_0$ in the vacuum at the inner side of the target. (b) Spectrum of HHG at $13.25T_0$, conforms to the power-law of ROM $I \propto (\omega/\omega_0)^{-8/3}$. The inset is the distribution of the reflected field E_x .

3.2. γ -ray Pulses Generation

Electrons escaping from the target surface contribute to the high-energy photon generation through NCS, before which, the electrons experience further accelerations under a different mechanism. As shown in Figure 3b,d, after the time t_2 , the energy increases mainly due to the positive work carried out by the *x*-direction electric field, namely, transiting from the incident laser action before t_2 to the reflected electromagnetic field action. Meanwhile, the momentum mainly increases in the *y*-direction (Figure 3c), suggesting that the electrons are mainly under the vacuum laser acceleration. At time t_4 and t_5 , one can observe the dramatic variation in momentum p_x , which is also reflected from the shake of the electron's trajectories and works carried out by the electric field. This momentum variation is comprehensible for the scattering between electrons and the counter-propagating attosecond electromagnetic pulse. Followed by the NCS, quantities of high energy photons are generated to constitute an attosecond γ -ray pulse.

Figure 4 demonstrates the photons' distribution, as well as characteristics, after all of the scatterings. γ -ray pulses asymmetrically distribute in the whole area, and a typical density profile along the pulse propagation direction shows a pulse duration FWHM $\approx T_0/10 = 267$ as (Figure 4b); in addition, the maximal photon energy can extend to 6 MeV (Figure 4d). The peak brilliance $> 10^{22}$ photons/(s·mm²·mrad²·0.1%BW). Furthermore, the directionality of photon propagations is also investigated, as shown in Figure 4c, where the photons generally propagate along the azimuthal angle around $\pm 90^{\circ}$ and $\pm 45^{\circ}$. The former is rational since the electron slices and the reflected electromagnetic field both propagate vertically before heading into collisions. With regard to the latter, it is probably due to the momentum modulation caused by the incident laser. Under the additional vacuum laser acceleration of the incident laser toward the positive *x*-axis direction, p_x of the escaped electrons gets enlarged, yielding the electrons, and EM pulses collide at an acute angle at around 45°. As a potential light source of the γ -ray, this fantastic directionality suggests that the direction of the γ -ray pulses can be manipulated by adjusting the cone target's open angle.



Figure 3. (Color online). (a) The electron trajectories during the emission of HHG. (b) The electron trajectories after leaving the target surface. (c) The variation in electron momentum p_x over time. (d) The work carried out by the electric field on the electrons. The values of t_1 , t_2 , t_3 , t_4 and t_5 are 14.30 T_0 , 14.74 T_0 , 15.37 T_0 , 15.90 T_0 , 16.37 T_0 , respectively.

Another characteristic of the γ -ray pulses lies in the asymmetries of the spatial (Figure 4a) and angular (Figure 4c,d) distribution. As a matter of fact, one can find that the pulses with $p_y > 0$ and $p_y < 0$ are alternately generated, which can be originated to the escape asymmetry of the electron slices (Figure 2a). Equation (1) shows the $\pi/2$ phase difference between the E_{\perp} in the upper side ($y > 12\lambda$) and lower side ($y < 12\lambda$), suggesting that the electron slices are alternately generated from the two sides with a $\pi/2$ phase difference. γ -ray generations influenced by this asymmetry may become macroscopically insignificant for the long incident laser pulse. However, for the few-cycle laser pulses, this asymmetry will significantly affect the whole photon distribution, and the carrier-envelope phase (CEP) is also a nonnegligible parameter, as the time and intensity of the γ -ray that is generated strongly rely on it. Consequently, the CEP of a few-cycle laser pulse can probably be deciphered by detecting the intensities of the γ -ray from the two sides, i.e., $p_y > 0$ and $p_y < 0$.



Figure 4. (Color online). (a) The density distribution of photons at $19.24T_0$. There are three bunches of photons around $y = 8.3\lambda_0$, $y = 15.15\lambda_0$ and $y = 16.15\lambda_0$. (b) The density distribution of photons around $y = 8.3\lambda_0$; the FWHM is $0.1T_0$ (267as). (c) The angular distribution of photons; the unit of radial scale is MeV. (d) The energy spectrum of photons; the cut-off energy is 6 MeV. $p_y > 0$ corresponds to the red curve, $p_y < 0$ corresponds to the green curve and the total momentum corresponds to the black curve.

To explain the significance of γ -ray generation via the NCS, we make a comparative simulation by taking away the top half of the cone target, which corresponds to a laser irradiating a planar target obliquely at an angle of 45°. All other parameters remain the same. Figure 5a,b demonstrates the electrons' behavior after leaving the target surface in the planar target case. The physical processes before t_3 in Figure 5a,b are similar with those in the cone target case, while there are obvious differences after t_3 . The momentum p_x at t_4 and t_5 varies weakly since there is no counter-propagating attosecond electromagnetic pulses, and the NCS process cannot occur. The photon spectrum presented in Figure 5c shows that the photon yield decreases significantly and the maximum photon energy is reduced to the *x*-ray range (100 KeV~1 MeV). The energy conversion efficiency of the laser to the photon for the cone target and planar target is 0.24% and 0.02%, respectively, with a 12-fold difference between them. Compared to the scheme in ref. [22], the energy conversion efficiency 0.24% is an order of magnitude higher, although a less intense laser is used. Therefore, this indicates that high-energy photons are produced by the NCS mechanism in our cone target scheme, and the scheme is more effective in γ -ray production.



Figure 5. (Color online). (a) The electron trajectories after leaving the target surface. (b) The variation in electron momentum p_x over time. (c) The energy spectrum of photons; the cut-off energy is less than 1 MeV. (**a**–**c**) are all in the planar target case. The values of t_1 , t_2 , t_3 , t_4 and t_5 are the same as those in the cone target case.

In addition, simulation results for five open angles of 30° , 60° , 90° , 120° and 150° show that both the cut-off energy and energy conversion efficiency of the photon beam have a maximum value at 90° , which can be seen from Figure 6. This is because, when the open angle is 90° , the reflected laser and the reversed electron beam collide head-on and the chance of the NCS is the greatest. In addition, Figure 6 shows that the energy conversion efficiency at 30° is instead larger than that at 60° . This is rational because the structure of the 30° cone target is closer to a cone channel, in which, more laser energy is transferred to the electrons [28], and the corresponding laser-to-photon energy conversion efficiency is increased, whereas the cut-off energy lies at a relatively low value.



Figure 6. (Color online). Cut-off energy of photons and laser-to-photon energy conversion efficiency for five different open angles $(30^\circ, 60^\circ, 90^\circ, 120^\circ, 150^\circ)$.

On the other hand, the γ -ray we obtain is of a higher energy and shorter FWHM compared to that of the two-laser scheme in ref. [29]. Despite the intensity of the laser we use being a little higher, our scheme requires only a single laser beam instead of the two lasers in ref. [29], which potentially has practical advantages due to the absence of the lasers' spatial collimation and delay setting. Furthermore, we use a different mechanism comparable to the one in ref. [30] that is based on the wakefield acceleration, but we obtain comparable γ -ray quantities, which indicates that our scheme is indeed an efficient alternative method for generating a high-quality γ -ray.

4. Conclusions

In conclusion, we have proposed a scheme to generate spatially separated attosecond pulses by irradiating a cone target with a *p*-polarized laser at an intensity of $a_0 = 30$. The laser irradiates on the cone's inner side and reflects as an emission of HHG. Meanwhile, quite a large amount of electrons escape out of the inner side under the action of the laser's ponderomotive force, Lorentz force and the ions' electrostatic force, after which, the escaped electrons collide with the counter-propagating attosecond electromagnetic pulses and quantities of high-energy photons are generated to constitute attosecond γ -ray pulses. The cut-off energy of the γ -ray is 6 MeV, and the FWHM of a single pulse can reach 267as; in particular, the corresponding peak brilliance >10²² photons/(s·mm²·mrad²·0.1%BW) is obtained. A series of comparative simulations show that the laser-to-photon energy conversion efficiency at the cone target is 12 times higher than that at the planar target, and the energy conversion efficiency and photon cut-off energy at the cone target at 90° are the highest compared with the others.

Studies on the effect of escaped electrons on the correction of the HHG power-law, the influence of CEP on distribution and the effects of other parameters, e.g., the laser intensity on γ -ray generation, is also valuable. They are beyond the scope of this paper and are worthy of being studied in the future.

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