High density γ-ray emission and dense positron production via multi-laser driven circular target

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Abstract
A diamond-like carbon circular target is proposed to improve γ-ray emission and pair production with a laser intensity of $8 \times 10^{22}$ W cm$^{-2}$ by using 2D particle-in-cell simulations with quantum electrodynamics. It is found that the circular target can enhance the density of γ-photons significantly more than a plane target, when two colliding circularly polarized lasers irradiate the target. By multi-laser irradiating the circular target, the optical trap of lasers can prevent the high energy electrons accelerated by laser radiation pressure from escaping. Hence, γ-photons with a high density of beyond 5000 $n_e$ are obtained through nonlinear Compton backscattering. Meanwhile, 2.7 $\times 10^{11}$ positrons with an average energy of 230 MeV are achieved via the multiphoton Breit–Wheeler process. Such an ultrabright γ-ray source and dense positron source can be useful in many applications. The optimal target radius and laser mismatching deviation parameters are also discussed in detail.

Keywords: $e^+e^-$ pairs production, γ-ray emission, Breit-Wheeler (BW) process, Compton backscattering (NCBS) process, particle-in-cell (PIC)

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

1. Introduction

With the rapid development of laser technologies, a laser intensity of $10^{22}$ W cm$^{-2}$ has been demonstrated [1]. Extreme laser intensities like $10^{23}$ W cm$^{-2}$ will be available in the next few years, which means the electron dynamics are approaching the nonlinear quantum electrodynamics (QED) regime [2, 3]. Such laser intensity will allow the study of bright γ-ray emission, $e^+e^-$ pair production, QED-cascade and particle acceleration in laboratories [4, 5]. A recent study showed that the QED-cascade saturation effect and the following nonlinear plasma dynamics including harmonic generation occur as laser intensity reaches $10^{24}$ W cm$^{-2}$, which could in principle be used to produce extreme dense γ-ray bursts and positron bunches [6, 7]. Intense γ-ray sources are useful for simulating the celestial process and extreme environments [8]. In recent decades, much research has focused on γ-ray emission and pair production [9–15]. At extremely high laser intensity, nonlinear Compton scattering is an important way for γ-rays to be emitted through colliding relativistic electrons with an intense laser pulse [16–19]. These high energy γ-photons colliding with lasers enable the laser energy to convert into $e^+e^-$ pairs via the multi-photon Breit–Wheeler (BW) process [20, 21].

Several schemes are proposed to generate bright γ-ray and pair production via nonlinear Compton scattering and the multi-photon BW process. One way is to enhance the laser
intensity by selecting appropriate polarized lasers [22–24] or/and focusing and redistributing the lasers’ energy [25–28]. Another way is to change the plasma target configuration, such as one or multiple laser interactions with near-critical-density plasma [29–34], solid Al target [35–40] or gas plasma [41, 42]. Positron beams with a small divergence angle [33] and desirable angular momentum [34] can be obtained in these ways. Among them, laser wakefield acceleration [43] and laser ponderomotive acceleration [44, 45] are generally used to realize electron acceleration and constraint. Recently, the radiation pressure acceleration (RPA) of ultra-thin foils has also been applied to γ-ray emission and dense e+e− pair production [46], as it is capable of obtaining high energy electrons and quasi-monoenergetic ion beams [47–50]. However, in this mechanism, the laser intensity of 5 × 10²³ W cm⁻² is too high to obtain experimentally and, on the other hand, the plane target cannot prevent the electrons from transverse escaping, while the radiative trapping [51] and pair plasma compression induced by standing wave fields can also be used to confine high-energy charged particles [6].

In this paper, a diamond-like carbon (DLC) circular target is presented as an alternative to prevent the electrons from escaping transversely. It is obvious that when the circular target is used, laser energy conversion efficiency to γ-photon is enhanced and the γ-photon number density is about twice as high as that of the plane target. Besides, the circular target allows an interaction with the multi-laser and, at the same time, the optical trap generated in situ can reduce the electrons escaping more efficiently. Eventually, an ultrabright γ-ray emission with a high density beyond 5000nₑ is obtained at 14T₀ (where T₀ is the laser period) under the laser intensity 8 × 10⁻²² W cm⁻², through the nonlinear Compton back-scattering (NCBS) process. Further, these 7.5 × 10¹⁴ photons with an average energy of 16 MeV, colliding with lasers can produce dense positrons with more than 20nₑ density via the multi-photon BW process. The total positron yield can be as high as 2.7 × 10¹¹, with an average energy of about 230 MeV.

The paper is organized as follows. Section 2 outlines the basic target configurations and simulation parameters. The γ-ray emission by two circularly polarized (CP) laser-driven targets is also discussed in detail. Section 3 examines the ultrabright γ-ray emission and e+e− pair production through RPA by four CP lasers irradiating a circular target. Among them, the optimal target radius and the deviation of mismatching lasers are also taken into account. Lastly, a brief summary is given in section 4.

2. Ultrabright γ-ray emission by two lasers irradiating a circular target

The 2D3V simulation results of ultrabright γ-ray emission by a two-laser-driven DLC target are performed via QED-PIC code EPOCH [52, 53].

The DLC foils are ideal materials for self-supporting targets in experiments due to their high tensile strength, hardness and heat resistance [54]. In our scheme, a circular DLC target as shown in figure 1(b) is used instead of the plane DLC target, as shown in figure 1(a) [46] to get brighter γ-rays and denser e+e− pairs through RPA. The DLC target is a plasma consisting of electrons, protons and full ionized carbon ions with charge state Z = 6 and mass mₑ = 12 × 1836mₑ, where mₑ is the electron mass. The density of the target is nₑ = 200nₑ, mixed with 20% protons in number density, where nₑ = mₑc²/4πe² (ω₀ is the frequency and −e is the charge) is the critical density of plasma. As figure 1 shows, the simulation box size is 20λ × 20λ with 2000 × 1400 grid cells. Two identical CP laser pulses are incident from the center of the left and right boundaries of the box simultaneously. Each laser has a peak intensity of 8 × 10²² W cm⁻² and rises in about 1T₀ and then retains the maximum amplitude for 9T₀, where T₀ = λ/c is the laser
period, \( \lambda = 1 \, \mu m \) is the wavelength of the laser and \( c \) is the speed of light. The laser is of Gaussian profile in the \( y \) direction with a spot size of \( 4 \, \mu m \) (full width at half maximum (FWHM)). When the laser intensity is \( 8 \times 10^{22} \, W \, cm^{-2} \), the optimal thickness and foil gap of the plane target for \( \gamma \)-ray emission and pair production have been studied in detail [46]. So, both targets in our scheme have a thickness of \( L = 0.25 \, \mu m \) and the coordinates of the target centre are \((x, y) = (10 \, \mu m, 0)\). The foil gap is \( G = 13.5 \, \mu m \) for the target and the radius is \( R = 5 \, \mu m \) for the circular target. Note that only the \( \gamma \)-photons, whose energy is larger than 1 MeV, are counted in the following simulations.

In the initial stage, the electrons, carbon ions and protons are separated and form a big charge separation field resulting in an inefficient acceleration of electrons due to the heavier carbon ions by using the DLC target. As time goes on, most of the laser waves penetrate through the target and begin to collide with the relativistic electrons accelerated by the opposite laser from the other side through RPA. At this point, high energy \( \gamma \)-photons are generated through NCBS. When the high energy \( \gamma \)-photons collide with the lasers, the \( e^+e^- \) pair is produced via the multi-photon BW process. For the plane target, the laser intensity along the axis increases since the laser is further focused in the inner surfaces as the target undergoes significant deformation. So, a large number of electrons escape from the foil, which results in a low density of \( \gamma \)-rays, as shown in figure 2(a). The circular target we proposed can enhance the \( \gamma \)-photon density to \( 800n_c \), which is about twice the \( \gamma \)-photon density of the plane target. There are two reasons for this enhancement. On the one hand, the circular target structure can slow down the focusing of the laser pulse and the increase in laser intensity, which will reduce the electrons escaping. On the other hand, the lasers pull the electrons out of the circular target continually and replenish the electron source when the foil deforms and \( \gamma \)-rays emit. Besides, the high density \( \gamma \)-ray, shown in figure 2(b), can sustain about \( 5T_0 \), which may become a stable \( \gamma \)-ray source in future laboratories.

The laser energy conversion efficiency to \( \gamma \)-photons for the plane target (the blue triangle curve) and the circular target (the red circular curve) is plotted in figure 2(c). The energy conversion efficiency of laser-to-photon for the plane target is about 6\%, which is comparable with the 3D simulation result of [46]. It is evident that the circular target can significantly enhance the energy conversion efficiency of laser-to-photon to about 9\% as time goes on. Due to the different structure, compared with the circular target, the plane target can focus the laser pulse more effectively, which means a larger laser intensity and the electrons can be accelerated to a higher energy. So, the disadvantage of the circular target is a lower cutoff energy of electrons.

While the lower \( \gamma \)-photon energy may reduce the possibility of \( e^+e^- \) pair production to some extent, the circular target irradiated by multiple lasers still has an obvious advantage that can be seen in the following study. It not only affords a stable and high density \( \gamma \)-ray source but also provides a chance to get higher density \( \gamma \)-photons and more \( e^+e^- \) pairs.

3. \( \gamma \)-ray emission and \( e^+e^- \) pair production by multi-laser driven circular target

In order to demonstrate the enhancement of ultrabright \( \gamma \)-ray emission and dense \( e^+e^- \) pair production by the multi-laser
driven DLC circular target, we performed the 2D3V simulation using the QED-PIC code EPOCH. The simulation parameters are the same as presented in section 2 except that two additional CP lasers are incident from the center of the up and down boundary of the simulation box and these two lasers are Gaussian profiles in the $x$ direction.

3.1. $\gamma$-ray emission

Figure 3 presents the transverse electric field (a)–(c), electron density (d)–(f) and photon density (g)–(i) distribution of the circular target at different stages. The probability rate for $\gamma$-ray emission in the QED regime is determined by a quantum invariant $\chi_e = (1/a_s) \sqrt{(\varepsilon_e E + P_e \times B)^2 - (P_e \cdot E)^2}$, where $a_s = eE/c \omega_0 = m_e c^2/h \omega_0$ is the normalized QED critical field, $E_\omega = m_e c^3/(he) = 1.32 \times 10^{18} \text{V/m}^{-1}$ is the Schwinger field [55], $\varepsilon_e = \gamma_e m_e c^2$ is the electron energy, $\gamma_e$ is the Lorentz factor, $P_e$ is the electron momentum, $E$ and $B$ are the electromagnetic fields. Through analyzing, we know that $\chi_e \approx 0$ and almost no high energy $\gamma$-photon is produced if the electrons interact with copropagating lasers. When the electrons collide with the counter-propagating lasers, the quantum invariant $\chi_e$ can be $\chi_e \approx 2 \gamma_e E/E_\omega$. Hence, the $\gamma$-ray emission is generated if $\chi_e \geq 1$, which relies on the electron energy and electric field intensity of lasers.

At the first stage, the initial circular target is distorted to be a four-cone structure by the four lasers. Some electrons are first pulled out from the inner wall of the target and then rapidly accelerated to high speed by the laser pressure, forming overdense relativistic electron layers, as shown in figure 3(d). A big charge separation field is formed, meanwhile, due to the heavy protons and heavier carbon ions of the DLC target materials which in turn pull ions forward. The accelerated electrons interact with the reflected laser waves resulting in $\gamma$-ray emission by NCBS, as seen in figure 3(g).

As shown in figure 3(b), the lasers in the cone top are further focused and the intensity is enhanced when the target is expanding. So, the central residual electrons of the target are pulled off, as shown in figure 3(e), and the relativistic transparency of the DLC target occurs now, which means the lasers will penetrate through the target and collide with the counter-propagating electrons at about $14T_0$. Through the NCBS, the $\gamma$-ray emission is enhanced resulting in an ultrabright $\gamma$-ray with a high peak density beyond $5000 m_e c$. As shown in figure 3(f), for the two-laser driven DLC circular target, the photon peak density can exceed $1900 m_e c$. This indicates that the peak density of photons is increased about 2.7 times when the other two lasers are injected on side. In addition, the high density $\gamma$-photons can sustain about 20 fs. One reason for these benefits is that the escaped electrons with transverse velocity will also interact with side lasers to realize the $\gamma$-ray emission enhancement. Another more important reason is that the optical traps created by multiple lasers prevent the electrons escaping from the region of maximum laser intensity.

Due to the limitation of our computer sources, here we only present a 2D optical trap with four lasers, in figure 4, which is a mimic of a real 3D optical trap formation by six
laser beams. Some striking features are kept in our 2D simulations. It was shown that the lattice-like magnetic field $B_z$ is formed and the intensity is enhanced as the lasers begin to overlap at $14T_0$. At $16T_0$, the lasers are fully overlapped and the magnetic field $B_z$ is enhanced from 300 MG to about 700 MG, which is beneficial for trapping electrons and maximising the $\gamma$-ray emission. It is obvious that the different lattice-like optical trap structures at different stages correspond to different lattice structures of density distributions of electrons and $\gamma$-photons, which can be seen by comparing figures 3 and 4. This confirms our judgement more efficiently that the optical traps created by multiple lasers are the main reason for $\gamma$-ray emission enhancement.

The lattice-like optical trap structure is diffused and the $B_z$ is reduced as well, as shown in figure 4(d). In this last stage, after the lasers penetrate across the central intersection area, the overlapping area of lasers would be reduced gradually. When the interaction continues, charged particles will move away from the center due to a weakened trapping effect of multiple lasers. So, the $\gamma$-photons produced always escape from the center, when the rate of central production becomes smaller than the rate of escape, which results in a low number density of electrons and $\gamma$-photons, as shown in figure 3(i). The growth rate of electrons and $\gamma$-photons number at different times is presented in figure 5(a). It can be seen from this that the total $\gamma$-photon number is $7.5 \times 10^{14}$, which is enhanced by over an order of magnitude compared to the $\gamma$-ray source in [46]. Besides, the average energy of the obtained $\gamma$-photons can be about 16 MeV.

Above all, $7.5 \times 10^{14}$ $\gamma$-photons are obtained via the multi-laser driven DLC circular target, whose average energy is about 16 MeV. The maximum density of the $\gamma$-ray can exceed 5000m$_c$ at $14T_0$, which can be seen as an extremely dense and ultrabright $\gamma$-ray source for future application. These high quality photons will also have a significant benefit for pair production in the multi-photon BW process.

3.2. Dense $e^+e^-$ pair production

In the QED region, the multi-photon BW process is a very important mechanism for pair production through photon–photon annihilation ($\gamma + n\hbar\omega \rightarrow e^+ + e^-$). The probability for pair production via the multi-photon BW process is determined by quantum parameter $\chi_\gamma = (1/a_0) \sqrt{(\varepsilon \cdot E + P_\gamma \times B)^2 - (P_\gamma \cdot E)^2} \simeq (2\hbar\omega_c/m_e c^2)E/E_\gamma$, here, $\varepsilon = \hbar\omega_c$, $P_\gamma = \hbar\omega_c / c$ (\omega_c is the photon frequency). So, the pair production depends on the photon’s energy $\hbar\omega_c$ and the electric field $E$ in the interaction zone.

Figure 5(c) illustrates the energy spectrum of $\gamma$-photons at different times. Here, due to Doppler red shift, the reflected laser is weakened so that the maximal value of $\gamma$-photons is only 380 MeV at the first stage, such as $12T_0$, which is not enough to produce $e^+e^-$ pairs. At the second stage, the maximal cutoff energy of $\gamma$-photons can be 850 MeV by NCBS while it will decrease since the high energy $\gamma$-photons are continually applied to the multi-photon BW process. The spectrum has a wide distribution and the average energy $\varepsilon_\gamma$ can be 16 MeV at $17T_0$. Here, the high photon energy can greatly enhance the possibility of pair production. As an example, figures 6(a) and (b) present the positron density distribution at $14T_0$ and $17T_0$, respectively. At $14T_0$, when high energy $\gamma$-photons and lasers collide, the positron yield...
starts being considerable. In the second stage, the positron density remains at about 20 $n_c$ and the maximum value can be 29$n_c$ at 17$T_0$, as figure 6(b) shows. These long-lasting and high-bunching positrons have good prospects for potential applications in future.

The energy spectrum of positrons at different times has also been plotted in figure 6(c). The maximum energy of positrons obtained can be as high as ~ GeV at 14$T_0$. However, these higher energy positrons also oscillate in the laser field and emit $\gamma$-rays, resulting in a decrease in cutoff energy as time goes on. Beyond that, although the positron energy spectrum has a tendency to be a Maxwellian spectral pattern, however, obviously more positrons are located at an energy of 200 MeV, which can be achieved through the present scheme.

The significant increase in positron number through this process is plotted in figure 6(d), which shows that the final
number of positrons is $2.7 \times 10^{11}$. Besides, the mean positron energy can be 230 MeV at $17T_0$. It should be noted that when calculating the number of positrons in the 2D PIC simulation by EPOCH, the default size of the third dimension automatically being 1 m in the routine is obviously inconsistent with the full 3D reality. Therefore, in order to mimic 3D reality as much as possible, we have used the size of the third dimension as 4 $\mu$m in the present study, according to the laser spot size as well as the positron distribution.

To make the entire process more intuitive, we also calculate the time-dependence of the laser efficiency on electrons, $\gamma$-photons and positrons. The general finding is that the laser energy conversion efficiencies to $\gamma$-ray and positrons have a rapid growth in the second stage. As time goes on, the total laser energy conversion efficiencies to $\gamma$-photons and positrons are about 27% and 0.2%, respectively, which is a really high exploitation of laser energy.

### 3.3. The effect of the target radius on $\gamma$-ray emission and $e^+ e^-$ pair production

In our previous simulations, the circular target radius is chosen as 5 $\mu$m. Actually, the radius of the circular target plays an important role in $\gamma$-ray emission and pair production in real application.

Figure 7(a) shows the peak number density of $\gamma$-photons, laser-to-electron and laser-to-photon energy conversion efficiency at $17T_0$ with different target radii. On the one hand, the number density of photons is the highest when the radius is 5 $\mu$m, which is comparable to the laser spot size. When the radius is small, the number and accelerating distance of electrons under target is reduced accordingly, which means a low energy of produced electrons resulting in a low rate for the $\gamma$-ray emission. However, if the radius is large, the transverse Rayleigh–Taylor-like instability develops quickly [56, 57], which will also lower the energy of electrons resulting in an undesirable $\gamma$-ray emission. So, the ultrabright $\gamma$-photons can be achieved when the laser field and circular structure collimate the electrons together. On the other hand, the laser-to-photon energy conversion efficiency is consider-able when $R = 5 \mu$m. It means that the optimal target radius is 5 $\mu$m for $\gamma$-ray emission when both the number and average energy of $\gamma$-photons are taken into account.

As figure 7(a) shows, when $R \geq 5 \mu$m, the peak number density decreases as $R$ increases. And the average energy of $\gamma$–photons also decreases when $R \geq 5 \mu$m, as seen in figure 7(b). The reason is that more high energy $\gamma$-photons are used for pair production by the multi-photon BW process, although the electrons accelerating and high energy $\gamma$-ray emission become more significant as the radius increases. Thus, as shown in figure 7(b), when $R \geq 5 \mu$m, the average energy of $\gamma$-photons decreases as $R$ increases and the number and average energy of positrons have a significant increase as $R$ increases. It is obvious that the positron yield and average energy are almost the minimum value when the number density of photons and laser-to-photon energy conversion efficiency are maximum, comparing figure 7(b) with figure 7(a). So, the circular target radius should be increased appropriately if it is designed for pair productions.

### 3.4. The effect of incident laser beam mismatching

In experiments, the deviation of incident lasers becomes a key issue for pair production. In order to check the influence of the mismatching of lasers on the $\gamma$-ray emission and pair production, we assume one laser is incident with a deviation $C$, where $C$ is a transverse offset compared to the initial ideal case.
The deviation of lasers will reduce the collision interaction of lasers and high energy $\gamma$-photons, which may decrease the probability of pair production. As figure 8(a) shows, the laser energy conversion efficiencies to electrons, $\gamma$-photons and positrons at $17T_0$ are diminished as $C$ increases. Besides, the number and peak density of positrons are also reduced as $C$ increases, as shown in figure 8(b). Above all, both the ultrabright $\gamma$-ray source and high quality positrons can be obtained if the deviation of lasers is controlled within 1 $\mu$m.

Besides, the laser intensity also plays an important role in the QED process. The $\gamma$-ray emission and positron production depend on the foil thickness and laser intensity significantly. The laser intensity should match the target thickness in order to ensure the target has sufficient acceleration and the light can be transmitted and interact with the target on another side, which has been discussed in detail in reference [46]. And the preplasma caused by the laser prepulse has a bad influence on the $\gamma$-ray emission and positron production, which also requires the target thickness to be adjusted.

4. Summary and conclusion

In summary, a DLC circular target is proposed in the present study to replace the plane target and enhance the $\gamma$-ray emission and $e^+e^-$ pair production, by using the 2D3V QED-PIC code EPOCH. When two counterpropagating lasers are incident from the center of the left and right boundaries of the simulation box and interact with the target, the circular target can enhance the laser-to-photon energy conversion efficiency by comparing the plane target. The density of $\gamma$-photons is increased to about twice that of the plane target, at $20T_0$. Moreover, when another two counterpropagating lasers are incident from the center of the up and down boundary of the simulation box, the overlap of multi-lasers will enhance the laser intensity and form a stable lattice-like optical trap. This optical trap can prevent the high energy electrons accelerated by RPA escaping from the central interaction zone. Eventually, $7.5 \times 10^{11}$ $\gamma$-photons with an average energy of 16 MeV are obtained through NCBS, which is an order of magnitude higher than the photon yield from the plane target. The maximum density of $\gamma$-photons can exceed $5000n_c$ at $14T_0$, which could be an ultrabright $\gamma$-ray source in future applications.

Compared with the two-laser-driven circular target, we found that the number and density of $\gamma$-photons have a nonlinear growth when another laser is incident. These high quality photons collide with lasers resulting in positrons with a density of above $20n_c$, via the multi-photon BW process. As time goes on, the total yield of positrons with an average energy of 230 MeV can be $2.7 \times 10^{11}$. Furthermore, the optimal radius of the circular target for $\gamma$-ray emission and pair production has also been analyzed and discussed respectively. For $\gamma$-ray emission, the optimal radius of the target should be 5 $\mu$m. However, the radius should be increased suitably if one needs more positrons. Lastly, the deviation of lasers is considered for real applications, and we found that there is almost no effect on $\gamma$-ray emission and pair production if the deviation of lasers is controlled within 1 $\mu$m.

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References

[1] Yanovsky V et al 2008 Opt. Express 16 2109
[2] Di Piazza A et al 2012 Rev. Mod. Phys. 84 1177
[3] Mourou G A et al 2006 Rev. Mod. Phys. 78 309
[4] Remington B A et al 2005 Plasma Phys. Control. Fusion 47 A191
[5] Rufini R et al 2010 Phys. Rep. 487 1
[6] Luo W et al 2018 Sci. Rep. 8 8400
[7] Luo W et al 2018 Plasma Phys. Control Fusion 60 044011
[8] Aharonian F et al 2005 Science 307 1938
[9] Avetissian H K et al 2002 Phys. Rev. E 66 016502
[10] Shen B F et al 2001 Phys. Rev. E 65 016405
[11] Chen H et al 2009 Phys. Rev. Lett. 102 105001
[12] Liang E P et al 1998 Phys. Rev. Lett. 81 4887
[13] Avetissian H K et al 1996 Phys. Rev. D 54 5509
[14] Shkolnikova P L et al 1997 Appl. Phys. Lett. 71 3471
[15] Berezhiani V I et al 2007 Phys. Lett. A 360 624
[16] Di Piazza A et al 2010 Phys. Rev. Lett. 105 220403
[17] Ta Phuoc K et al 2012 Nat. Photon 6 308
[18] Sarri G et al 2014 Phys. Rev. Lett. 113 224801
[19] Sakai Y et al 2011 Phys. Rev. Accel. Beams 14 120702
[20] Breit G et al 1934 Phys. Rev. 46 1087
[21] Nikishov A I and Ritus V I 1964 Quantum processes in the field of a plane electromagnetic wave and in a constant field Sov. Phys. JETP 19 529-41
[22] Gelfer E G et al 2015 Phys. Rev. A 92 022113
[23] Yuan T et al 2017 Phys. Plasmas 24 063104
[24] Marija V et al 2017 Plasma Phys. Control. Fusion 59 014040
[25] Bulanov S S et al 2010 Phys. Rev. Lett. 104 220404
[26] Gonorov A et al 2014 Phys. Rev. Lett. 113 014801
[27] Esirkepov T Z et al 2015 Phys. Lett. A 379 2044
[28] Kirk J G 2016 Plasma Phys. Control. Fusion 58 085005
[29] Liu J J et al 2016 Opt. Express 17 15978
[30] Huang T W et al 2017 Appl. Phys. Lett. 110 021102
[31] Zhu X L et al 2016 Nat. Commun. 7 13686
[32] Brady C S et al 2013 Plasma Phys. Control. Fusion 55 124016
[33] Zhu X L et al 2019 Matter Radiat. Extremes 4 014401
[34] Zhu X L et al 2018 New J. Phys. 20 083013
[35] Ridgers C P et al 2012 Phys. Rev. Lett. 108 165006
[36] Luo W et al 2015 Phys. Plasmas 22 063112
[37] Chang H X et al 2015 Phys. Rev. E 92 053107
[38] Liu W Y et al 2017 Phys. Plasmas 24 103130
[39] Liu W Y et al 2018 Chin. Phys. B 27 105202
[40] Luo W et al 2018 Plasma Phys. Control. Fusion 60 095006
[41] Liu J X et al 2016 Plasma Phys. Control. Fusion 58 125007
[42] Lobet M et al 2017 Phys. Rev. Accel. Beams 20 043401
[43] Liu J X et al 2017 Plasma Sci. Technol. 19 015001
[44] Li H Z et al 2017 Opt. Express 25 21583
[45] Hu L X et al 2015 Phys. Plasmas 22 033104
[46] Li H Z et al 2017 Sci. Rep. 7 17312
[47] Henig A et al 2009 Phys. Rev. Lett. 103 245003
[48] Macchi A et al 2009 Phys. Rev. Lett. 103 085003
[49] Lv C et al 2017 Phys. Plasmas 24 033122
[50] Zhou W J et al 2018 Phys. Rev. Accel. Beams 21 021301
[51] Ji L L et al 2014 Phys. Rev. Lett. 112 145003
[52] Ridgers C P et al 2014 J. Comput. Phys. 260 273
[53] Duclos R et al 2011 Plasma Phys. Control. Fusion 53 015009
[54] Liechtenstein V K et al 1997 Nucl. Instrum. Methods Phys. Res. 397 140
[55] Schwinger J 1951 Phys. Rev. 82 664
[56] Chen M et al 2011 Phys. Plasmas 18 073106
[57] Wang W Q et al 2015 Phys. Rev. E 92 063111