Linear Breit-Wheeler process driven by compact lasers

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We report a proposal to observe the two-photon Breit-Wheeler process in plasma driven by compact lasers. A high-charge electron bunch can be generated from laser plasma wakefield acceleration when a tightly focused laser pulse propagates in a subcritical density plasma. The electron bunch scatters with the laser pulse coming from the opposite direction and resulting in the emission of high brilliance x-ray pulses. In a three-dimensional particle-in-cell simulation with a laser pulse of $\sim$10 J, one could produce an x-ray pulse with a photon number higher than 3×10^{11} and brilliance above 1.6×10^{23} photons/s/mm^2/mrad^2/0.1% BW at 1 MeV. The x-ray pulses collide in the plasma and create more than 1.1×10^5 electron-positron pairs per shot. It is also found that the positrons can be accelerated transversely by a transverse electric field generated in the plasma, which enables the safe detection in the direction away from the laser pulses. This proposal enables the observation of the linear Breit-Wheeler process in a compact device with a single shot.

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I. INTRODUCTION

The Breit-Wheeler (BW) process, which was first proposed in theory by Breit and Wheeler in 1934 [1], could create matter and antimatter from the collision of two photon quanta. Normally, the BW process includes a two-photon process ($\gamma + \gamma \rightarrow e^- + e^+$) and multiphoton process ($\gamma + n\gamma \rightarrow e^- + e^+$). The BW process is recognized as a fundamental component of quantum electrodynamics theories [2]. Hence, the experimental study of the BW process could provide important tests for the fundamental physics. Nevertheless, due to the lack of high brilliance and energetic photon sources, Breit and Wheeler even declared in 1934 that it was hopeless to observe pair creation in the laboratory. In the past 40 years, the CPA (Chirped Pulse Amplification) technology [3] has greatly promoted the development of high-power laser technology [4], and a laser intensity above 10^{23} W/cm^2 has been realized most recently [5], which promoted the development of quantum dynamics, quantum electrodynamics, nuclear and particle physics, and strong field physics [6–9]. At such intensity, it is very likely to emit high-energy photons above GeV [10]. The multiphoton BW process has been experimentally demonstrated in 1997 through the scattering between high-energy photons of GeV and several laser photons [11,12]. In the past decade, increasing attention has been paid to experimentally study the multiphoton BW process with high-power PW lasers [10,13–16]. Numerical simulations have demonstrated the potential to generate 10^{11} electron-positron pairs per shot by using 10-PW lasers [17]. In another study, the optimal conditions for BW pair production were investigated, considering a fixed laser energy but varying the spatiotemporal shape of the laser [18]. The nonlinear BW process has also been observed in collisions with oriented crystals in the latest research [19,20]. Moreover, a recent observation of the linear Breit-Wheeler process by the STAR Collaboration has shown linear BW using low-virtuality photons [21].

On the other hand, the two-photon BW process involving real photons, which is a fundamental phenomenon in quantum electrodynamics theories, has never been observed in the laboratory [9]. The difficulty in experimentally observing the two-photon BW process lies in the absence of high brilliance γ-ray pulses [22] together with the challenge in extracting useful signals from noise [23–25]. In the past few years, various theoretical scenarios have been proposed to observe the signal of the two-photon BW process. Pike *et al.* presented the first photon-photon collider in a vacuum hohlraum [23]. Ribeyre *et al.* proposed an experimental approach using MeV photon sources driven by $\sim$10 PW lasers [24]. Micieli *et al.* designed a photon-photon collider based on conventional Thomson γ-ray sources [26]. Yu *et al.* put forward an approach utilizing collimated and wide-bandwidth γ-ray pulses [25]. Wang *et al.* systematically studied the two-photon pair production using a structured target in three-dimensional particle-in-cell (3D-PIC) simulations [27]. He *et al.* discussed the dominance condition of γ-γ collision in plasma driven by high-intensity lasers [28]; at the same time they found that the

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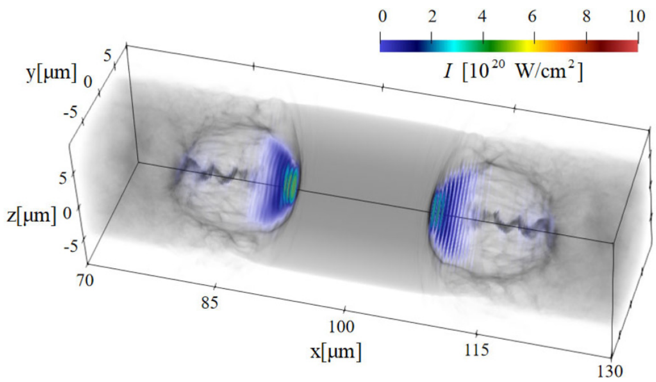

FIG. 1. Schematics for the setup of photon-photon collision in plasma driven by compact lasers of ∼10 J. The laser pulses, which are tightly focused to an intensity above 10^{21} W/cm^2, generate wakefield acceleration for the formation of high-charge electron bunches (∼10 nC) in the sub-critical density plasma of ∼200 μm. There are two stages that can generate high brilliance γ-ray pulses. Betatron x ray can be radiated when the electron bunches oscillate transversely in the plasma bubble during the stage of electron acceleration. Nonlinear Thomson scattering occurs when the electron bunches collide with the laser pulse coming from the opposite direction. The high brilliance γ-ray pulses collide in the plasma and create more than 1×10^5 electron-positron pairs.

longitudinal plasma electric field drove the photon emission in the backward direction, thus enabling the linear BW process with a single laser. [29]. Golub *et al.* utilized the interaction between bremsstrahlung photons with an energy of a few GeV and x-ray free-electron laser photons in the keV range, which furnished enough energy for the linear BW process to occur [22]. Zhao *et al.* investigated the polarization characteristics of linear BW process in a polarized γ-γ collider [30]. In brief, the above solutions require a large machine like a laser near 10 PW or a conventional accelerator. However, these large machines demand considerable financial investments and extensive space to accommodate them. Therefore, it is important to study the scenario of performing the experiment on a more compact and widely available laser.

Most recently, a scientific team led by the UK is attempting to conduct the experiment of photon-photon collision on a compact platform [31]. Due to the generation of only around 7×10^7 photons per shot, more than 10^9 shots are needed to observe the linear BW process on this platform, and it could be reduced to 5000 shots by increasing the electron energy. However, laser-plasma interactions are inherently characterized by a high degree of instability and variability. In multishot scenarios, each shot can have significant differences due to minor fluctuations in experiment. Hence, further developments of such a compact platform should significantly reduce the number of shots to a few hundred or even to a single one, making this process more achievable.

In this paper, we propose a scheme to observe the two-photon Breit-Wheeler process in a single shot through the interaction between a subcritical density plasma (SCDP) and compact lasers. The laser pulses were tightly focused to a spot of several micrometers so they can achieve an intensity higher than 10^{21} W/cm^2 despite the relatively low power of hundreds of TW, which can be easily achieved on a compact platform. The two counter-propagating lasers were spatially aligned using an alignment wire, with beam splitter and mirrors used to derive them from a single source, ensuring their temporal synchronization. When the laser pulses propagate through the SCDP, laser plasma wakefield acceleration (LPWA) [32,33] can be generated and high-charge electron bunches would be generated. Nonlinear Thomson scattering [34,35] occurs when the electron bunch scatters with the laser pulse coming from the opposite direction, resulting in the emission of high brilliance x-ray pulses. 3D-PIC simulation with laser pulses of ∼10 J and a SCDP of $0.1n_c$ demonstrates that it is possible to generate high-charge electron bunches of ∼10 nC, x-ray pulses with a photon number higher than 3×10^{11}, and brilliance above 1.6×10^{23} photons/s/mm^2/mrad^2/0.1% BW at 1 MeV. Shortly after the scattering, the x-ray pulses collide in an ultrasmall transverse area and create more than 1×10^5 electron-positron pairs in a single shot. It is also found that the positrons can be deflected by a transverse electric field generated in the plasma, which enables the safe detection in the direction away from the laser pulses. Therefore, the observation of the two-photon Breit-Wheeler process can be realized on a much more compact device in a single shot.

II. SCHEME DESIGN AND SIMULATION SETUP

With the development of target manufacturing technology, it has become possible to produce SCDP in the laboratory using carbon nanotubes [36]. In the past few years, SCDP has been widely used to produce high-quality charged particles [37–39] and radiation [40–43]. Recently, we reported a regime in which a high-charge electron bunch was generated through a combined process of LPWA and direct laser acceleration in a SCDP, driven by a tightly focused laser pulse [44]. In this regime, an electron bunch with a charge higher than 10 nC could be generated using a compact laser.

Following the route of generating a high-charge electron bunch, we propose a scheme to observe photon-photon collision in plasma driven by compact ultrashort pulse lasers as shown in Fig. 1. Two laser pulses with the energy of ∼10 J are tightly focused to a spot of several micrometers. The laser pulses which irradiate on a ∼200 μm SCDP from opposite directions result in the generation of high-charge electron bunches dominated by LPWA [44]. When the electron bunch collides with the laser pulse from the opposite direction, nonlinear Thomson scattering [34,35] will take place, inducing the radiation of a high brilliance γ-ray pulse. In this setup, the laser pulse should collide with the electron bunch before being fully depleted. Since the electron bunch is closely behind the driving laser, γ-ray photons can collide with that scattered from the electron bunch on the other side in a very short duration. Therefore, one could achieve photon-photon collision in a spot of several micrometers.

We used 3D-PIC code EPOCH3D [45] to explore the generations of the high-charge electron bunches and γ-ray pulses, as well as the dynamic behavior of positrons in the plasma. The simulation box X × Y × Z = 200 μm × 24 μm × 24 μm was divided into 4000 × 240 × 240 cells. The driving lasers, each producing a pulse of 21.3 fs duration at FWHM (full width at half maximum), operated at a wavelength $\lambda_0 =$ 800 nm and had a Gaussian spatial profile, a $\sin^2$ temporal

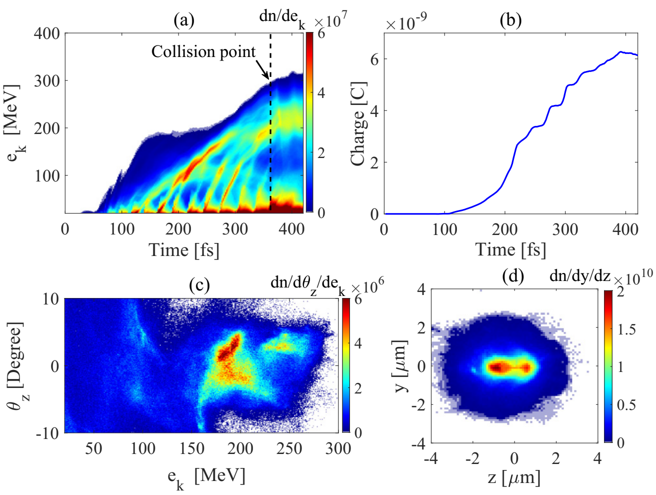

FIG. 2. 3D-PIC simulation results of laser wakefield acceleration in the 200 μm SCDP driven by the laser pulses. (a) Evolution of the electron kinetic energy spectra with simulation time to 420 fs. (b) The charge of a single electron bunch (>100 MeV) as a function of the simulation time. (c) The spectral-angular distribution and (d) the spatial distribution of the electrons at 350 fs.

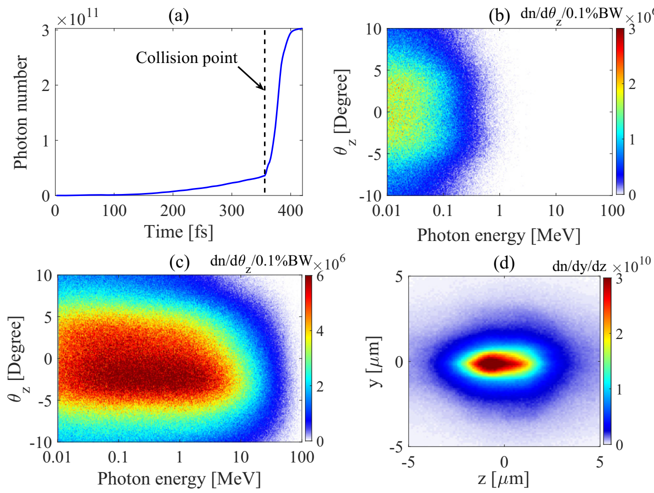

FIG. 3. 3D-PIC simulation results of x-ray photons (>10 keV) generated from the 200 μm SCDP. (a) The photon number as a function of the simulation time. The spectral-angular distribution of the x-ray photons (b) at 350 fs and (c) 420 fs. (d) The spatial distribution of the x-ray photons at 420 fs.

profile, and a Z-axis polarization. These pulses were tightly focused to a waist $w_0 = 2.4$ μm with a normalized intensity $a_0 = 40$. The on target power of each pulse was about 10 J which could be exported by a compact laser system [4]. Under the laser pulses of ultra high intensity, the SCDP could be fully ionized to electrons and C^{6+}. In the simulations, a cylindrical SCDP was modeled with an electron density of $n_e = 0.1n_c$, a length of 196 μm and a radius of 12 μm. Here, n_c is the critical density of the plasma. Twenty (four) macroelectrons (C^{6+}) were initialized into each cell.

III. ELECTRON ACCELERATION AND γ-RAY GENERATION

Figure 1 shows the distributions of laser intensity and electron density at 330 fs, from which one can see two plasma cavities and the accelerated electron bunches in the wakefield. As demonstrated in previous work [44], LPWA could dominate the electron acceleration in the SCDP when the normalized laser intensity a_0 is larger than 20. Figure 2(a) illustrates the evolution of the electron energy spectra in the first 420 fs. It demonstrates that the electrons can be accelerated to ∼300 MeV in a distance less than 100 μm, corresponding to an acceleration gradient of roughly 3 TV/m. The figure clearly shows a continuous capture of electrons and indicates that the beam-loading effect [46] is no longer working under this strong nonlinear condition, leading to the charge of the electron bunch exceeding 6 nC at 420 fs as shown in Fig. 2(b). Since most of the laser has not been depleted yet, more electrons could be captured by the wakefield and accelerated to higher energy than that shown in Fig. 2(b) in the case of a longer SCDP.

The production of electron-positron pairs is a function of the photon number, the collision area size, and the photon-photon cross-section area for BW process. Comparing with the normal LPWA [47,48], we pursued high-charge and collimated electron bunches at the cost of their energy spread and divergence angle in this paper. High-charge electron bunches could radiate a high-flux photon pulse which is a prerequisite for enhancing the electron-positron pair production. Meanwhile, the impacts of energy spread and divergence angle on the pair production is virtually negligible in this proposal. Figure 2(c) shows the spectral-angular distribution of the electron bunch before the collision, the divergence angle in the polarized direction $\theta_z \sim 5^\circ$ ($\theta_y \sim 2^\circ$) is larger than that in normal LPWA [47,48]. The divergence angle of the electron bunch could be further reduced assuming a longer acceleration distance. The transverse area of the electron bunch is smaller than the spot of the laser from the opposite direction, as shown in Fig. 2(d), making sure of enough overlapping space during collision for nonlinear Thomson scattering.

In the simulation, the electron bunch and the laser pulse collided at 358 fs. Before the collision, Betatron radiation [49–51] dominates the generation of the x-ray photons. There were 3.6×10^{10} x-ray photons (>10 keV) in the simulation box at 350 fs. This number is smaller than the actual generated number since the photons with a large divergence angle had already moved out of the simulation box and failed to be counted. From the spectral-angular distribution of the x-ray photons shown in Fig. 3(b), one can see that most of the photons have energy less than 100 keV and the divergence angle is $\theta_z \sim 7.2^\circ$. Nonlinear Thomson scattering takes place from 358 to 400 fs, resulting in the generation of more than 2.65×10^{11} x-ray photons (>10 keV) during the collision, as displayed in Fig. 3(a). The photon generation duration time suggests that only a small portion of the laser pulse contributed to electron acceleration.

Figure 3(c) shows the spectral-angular distribution of the x-ray photons after collision. It is found that the photon maximum energy has been significantly enhanced and the divergence angle was reduced to $\theta_z \sim 6.3^\circ$. Since a large number of photons had energy higher than 0.511 MeV, which is the threshold energy for electron-positron pair generation in photon-photon collision [1,11], the generation of an electron-positron pair through the two-photon BW process becomes possible. In the photon-photon collision, one could significantly increase the number of electron-positron pairs by making the photon-photon collision in a smaller transverse area. The spatial distribution of the photons shown in Fig. 3(d) indicates that the transverse area of the photon bunch is 3.8 μm^2. Then we can calculate the brilliance at 1 MeV, yielding a value of greater than 1.6×10^{23} photons/s/mm^2/mrad^2/0.1% BW. Despite the lack of a significant advantage in brightness, this photon bunch has a much smaller light spot compared to the previous Thomson light source with SCDP [41]. This characteristic is more advantageous for photon-photon collision.

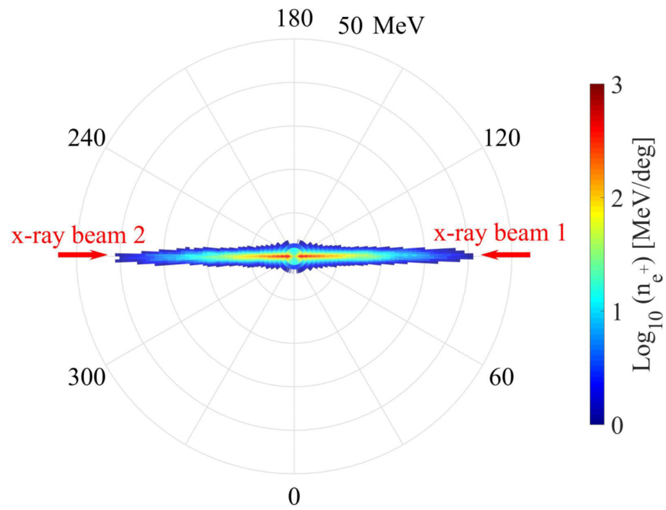

FIG. 4. The angular-spectrum distribution of the positrons in the laboratory frame calculated from the photon-photon collision in the 200 μm SCDP.

IV. PHOTON-PHOTON COLLISION

After obtaining the spectral-angular distribution of the x-ray photon shown in Fig. 3(c), we adopt the method of the macrophoton [25] to calculate the electron-positron pair creation. In the photon-photon collision for electron-positron pair creation, the threshold condition is

$$S = \frac{\varepsilon_{\gamma_1}\varepsilon_{\gamma_2}(1-\cos\theta_c)}{2(m_e c^2)^2} \geqslant 1, \tag{1}$$

where θ_c is the collision angle, ε_{γ_1} and ε_{γ_2} are the average energies of the macrophotons, m_e is the rest mass of the electron, and c is the vacuum light speed. In each collision between the macrophotons above the threshold condition, a macropair will be generated. The weight value of the macropair can be expressed as

$$w_{\text{pair}} = \frac{w_{\gamma_1} w_{\gamma_2} \sigma_{\gamma_1\gamma_2}}{S_c}, \tag{2}$$

where w_{γ_1} and w_{γ_2} are the weight value of the macrophotons, S_c is the transverse size of the cross-sectional area of the photon bunches, the cross-section $\sigma_{\gamma_1\gamma_2}$ of the BW process is [1]

$$\sigma_{\gamma_1\gamma_2} = \frac{\pi}{2} r_0^2 (1-\beta^2)\left[(3-\beta^4)\ln\left(\frac{1+\beta}{1-\beta}\right) - 2\beta(2-\beta^2)\right]. \tag{3}$$

Here $\beta = (1-1/S)^{1/2}$ and r_0 is the electron classical radius. After the collision, the energy of the photon is shared evenly between the electron and the positron, so we can calculate the energy ε_{ec} (ε_{pc}) and momentum $\vec{p}_{ec}$ ($\vec{p}_{pc}$) of the electron (positron) in the center-of-mass frame. Then, we can get the energy $\varepsilon_e(\varepsilon_p)$ and momentum $\vec{p}_e$ ($\vec{p}_p$) in the laboratory frame through Lorentz transformation [25].

In this proposal, the positrons can be created through the photon-photon collision in the SCDP as shown in Fig. 1. From the simulation, it is found that the effective photon-photon collision time is from ∼370 fs to ∼410 fs, and the effective transverse area for collision S_c is less than 3.0 μm^2. Then we used x-ray pulses with similar parameters shown in Fig. 3 to calculate the creation of the electron-positron pair. In the calculation, 1.1×10^5 electron-positron pairs could be created and the angular-spectrum distribution of the positrons was plotted in Fig. 4. Since wide bandwidth and collimated x-ray pulses [25] were used here, the created positrons had a small divergence angle of 4°.

The background signal comes from the Trident [52], Bethe-Heitler [53], and Triplet [54] processes. The noise from the Trident process is nearly perpendicular to the signal direction, and only the noise produced in the collision region will enter our detector [16]. We could calculate the production of Bethe-Heitler and Triplet processes using the method in Refs. [25,28]. It is calculated that the pair production of the background Bethe-Heitler and Triplet processes is 7.2×10^2 and 1.0×10^2, respectively, with $a_0 = 40$, which is smaller than the Breit-Wheeler signal by more than two orders of magnitude. Further calculation reveals that the pair production at the collision angle $\theta_c = 170°$ is 1.07×10^5, which is only slightly reduced compared to 180°. Therefore, utilizing an offset collision angle can effectively mitigate the problem that the lasers are being shot at each other through the plasma channel, ensuring the integrity and safety of the experimental setup.

From the evolution of the electron kinetic energy spectra shown in Fig. 2(a), one can see that the plasma length significantly affects the results of electron acceleration. In the case of a short length plasma, the electrons cannot be effectively accelerated, leading to a substantial reduction in both photon number and pair number. For longer plasma, most of the laser pulses has been consumed before the nonlinear Thomson scattering, leaving a very small portion of the laser pulses for scattering. Hence, there should be an optimal plasma length for the generation of an x-ray bunch. In the simulations, the plasma length was varied from 100 μm to 300 μm to examine the impact on photon number and pair number. As shown in Fig. 5, the photon number increased with the plasma length from 1.5×10^{11} to a peak of 3.4×10^{11} at a plasma length of 260 μm, then decreased to 3.1×10^{11} at 300 μm. Simultaneously, the pair number also experienced a rise from 1.3×10^4 to a peak of 1.3×10^5 at 240 μm before declaring to 9×10^4 at 300 μm. Therefore, we can infer that the optimal plasma length interval is between 240 μm and 260 μm.

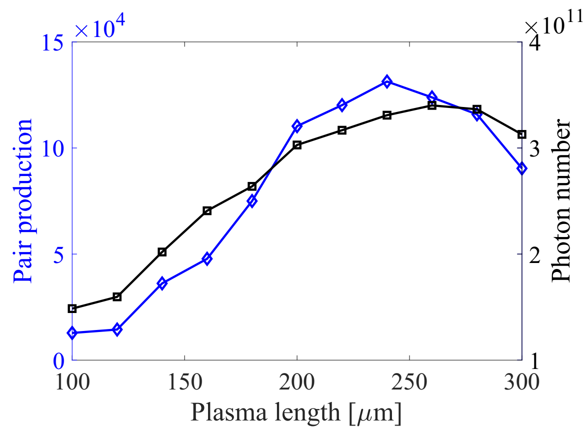

FIG. 5. The effect of the plasma length on x-ray photon number and pair production by varying the plasma length from 100 to 300 μm.

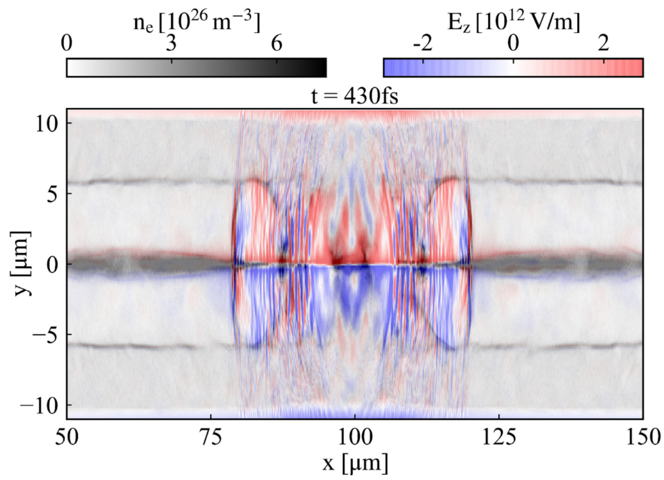

FIG. 6. The electron number density distribution and transverse field at 430 fs from 3D-PIC the simulation of ∼200 μm SCDP.

In addition, a series of 3D simulations were performed to investigate the influence of the laser normalized intensity a_0 on the x-ray photon number and pair number. In the simulations, a_0 was varied from 25 to 80 and n_e was adjusted according to the scaling law of LPWA [55], while the SCDP length and the laser pulse waist were fixed to 200 μm and 2.4 μm. respectively. From the simulation results listed in Table I, it is found that the photon number is proportional to $a_0^{2.4}$ and the pair number is proportional to $a_0^{5.0}$.

V. DYNAMICS OF THE POSITRONS IN SCDP

Towards the demonstration of photon-photon collision in the laboratory, the prerequisite is the ability to detect positrons in the experiments [25]. Diagnosing charged particles plays a crucial role in laser-plasma experiments conducted at superintense laser facilities [56]. This section investigates the potential diagnostic methods by exploring the dynamics of positrons in a 3D-PIC simulation of ∼200 μm SCDP. The simulation reveals that a strong transverse electric field will be generated during the collision. This field prompts a large number of electrons to move out of the collision area from the transverse direction and suppresses the positrons moving away until ∼410 fs. Figure 6 shows the electron number density distribution and transverse field at 430 fs. From this figure, one can see that there is a quasistatic transverse electric field of $10^{12}\mathrm{V/m}$ in the plasma channel. This electric field could accelerate the positrons out of the collision area from the transverse direction.

Then, we inputted the full information of the created positrons into the simulation, and made the positrons to move self-consistently in the plasma starting from 400 fs. Since the density of the positron is much smaller than that of electrons and ions, the impact of positrons on the fields can be ignored. From the simulation, it is found that the positrons begin to experience transverse acceleration from 410 fs, and most of the positrons could be accelerated off the plasma channel before ∼450 fs. Figure 7 shows the angular-spectrum distribution of the positrons at 440 fs. The figure shows that most of the positrons could be accelerated to ∼12.4 MeV in directions divergent from the transmission direction of the laser pulses. Hence, this proposal could enable the safe detection of positrons in the direction away from the laser pulses.

TABLE I. The effect of the laser normalized intensity a_0 on x-ray photon number and pair production by fixing the SCDP to 200 μm and laser pulse waist w_0 to 2.4 μm.

Laser a_0	n_e	Photon number	Pair number
25	$0.1n_c$	6.2×10^{10}	2.5×10^3
30	$0.1n_c$	1.8×10^{11}	5.7×10^4
40	$0.1n_c$	3.0×10^{11}	1.1×10^5
60	$0.3n_c$	9.8×10^{11}	1.2×10^6
80	$0.3n_c$	1.8×10^{12}	5.0×10^6
160	$0.8n_c$	8.6×10^{22}	1.1×10^8

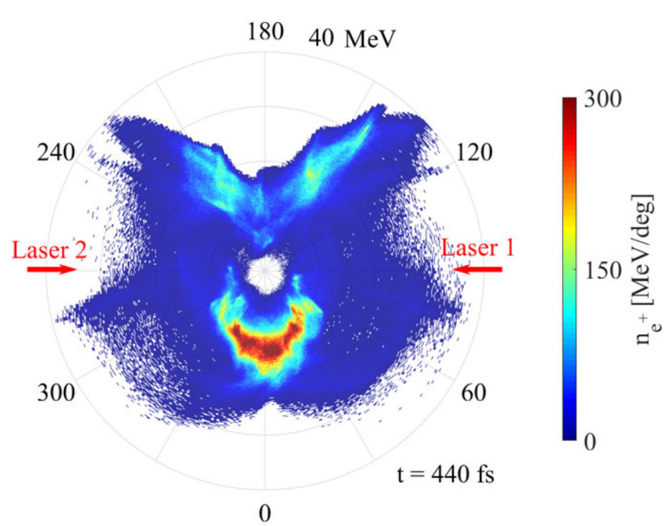

FIG. 7. The angular-spectrum distribution of the positrons in the laboratory frame at 440 fs. The positrons are accelerated transversely by the quasistatic transverse electric field. The central energy of the positrons is ∼12.4 MeV.

VI. SUMMARY

In summary, we propose a scheme to observe the two-photon Breit-Wheeler process in a single shot utilizing tightly focused 100s TW lasers which can be easily obtained on compact platforms. The interaction between the laser pluses and a SCDP generates two high-charge electron bunches of 6 nC with an energy of 300 MeV. When the electron bunch collides with the laser pulses, and nonlinear Thomson scattering [34,35] takes place, resulting in the production of high brilliance x-ray pulses, whose photon number is higher than 3×10^{11}, and brilliance is above 1.6×10^{23} photons/s/mm^2/mrad^2/0.1% BW at 1 MeV. The x-ray pulses collide within a spot about 2 μm and create more than 1.1×10^5 electron-positron pairs. The optimal plasma length is around 250 μm for a given a_0, while the photon number and pair number are proportional to $a_0^{2.4}$ and $a_0^{5.0}$, respectively. A 3D-PIC simulation demonstrates that the positrons can be accelerated by a strong transverse field and move away from the plasma channel. This scheme solves the key challenges of experimentally observing two-photon Breit-Wheeler process on compact platforms, particularly the limitation of generating electron-positron pairs in a single shot.

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