GeV-level γ-ray and positron beams produced by collisions of multi-PW laser with high-energy electron beam

Authors: Su, Ms. Wan-Qing, Ma, Dr. Chun-Wang (Nuclear physics), Cao, Dr. Xiguang, Zhang, Dr. GuoQiang, Dr. Yuting Wang, Ma, Dr. Chun-Wang (Nuclear physics)

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Abstract

Based on collisions between the 100 PW laser and 8 GeV superconducting linear accelerator under construction at the Shanghai High Repetition Rate X-ray Free Electron Laser and Extreme Light Facility (SHINE), the generation of GeV-level γ-ray and positron beams is proposed according to particle-in-cell simulations. Key processes considered involve nonlinear inverse Compton scattering for γ-ray generation and the multiphoton Breit-Wheeler process for electron-positron pair production. Regardless of laser polarization, the simulations indicate that γ-ray beams achieve energies up to 8 GeV, brilliance of approximately 10^{27} photons/$(\mathrm{s}\cdot\mathrm{mm}^2\cdot\mathrm{mrad}^2)$, and emittance as low as 0.1 $\mathrm{mm}\cdot\mathrm{mrad}$, while positron beams attain energies up to 7 GeV, brilliance of approximately 4×10^{24} positrons/$(\mathrm{s}\cdot\mathrm{mm}^2\cdot\mathrm{mrad}^2)$, and emittance as low as 0.1 $\mathrm{mm}\cdot\mathrm{mrad}$. Various applications could benefit from these potential high-energy γ-ray and positron beams at SHINE, including fundamental physics validation of strong-field quantum electrodynamics theory, nuclear physics, nuclear astrophysics, imaging, among others.

Full Text

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Wan-Qing Su[123], Chun-Wang Ma[14]†, Xi-Guang Cao[235]‡, Guo-Qiang Zhang[235], and Yu-Ting Wang[1]

[1]School of Physics, Henan Normal University, Xinxiang 453007, China
[2]Shanghai Advanced Research Institute, Chinese Academy of Sciences, Shanghai 201210, China
[3]Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai 201800, China
[4]Institute of Nuclear Science and Technology, Henan Academy of Sciences, Zhengzhou 450015, China
[5]University of Chinese Academy of Sciences, Beijing 100049, China

Based on collisions between the 100 PW laser and 8 GeV superconducting linear accelerator under construction at the Shanghai High Repetition Rate X-ray Free Electron Laser and Extreme Light Facility (SHINE), we propose the generation of GeV-level γ-ray and positron beams according to particle-in-cell simulations. Key processes considered include nonlinear inverse Compton scattering for γ-ray generation and the multiphoton Breit-Wheeler process for electron-positron pair production. Regardless of laser polarization, the simulations indicate that γ-ray beams achieve energies up to 8 GeV, brilliance around 10^{27} photons/(s $\cdot$ mm^2 $\cdot$ mrad^2), and emittance as low as 0.1 mm $\cdot$ mrad, while positron beams attain energies up to 7 GeV, brilliance around 4×10^{24} positrons/(s $\cdot$ mm^2 $\cdot$ mrad^2), and emittance as low as 0.1 mm $\cdot$ mrad. Various applications could benefit from these potential high-energy γ-ray and positron beams at SHINE, including fundamental physics for strong-field quantum electrodynamics theory validation, nuclear physics, nuclear astrophysics, imaging, and other areas.

Keywords: γ-ray source, positron beam, nonlinear inverse Compton scattering, multiphoton Breit-Wheeler process, ultra-intense ultra-short laser, particle-in-cell

INTRODUCTION

The Shanghai High Repetition Rate X-ray Free Electron Laser and Extreme Light Facility (SHINE) will deliver a photon beam with energy spanning from 0.4 to 25 keV, leveraging its MHz-level high repetition rate and femtosecond-level ultra-short pulses to achieve exceptionally high average and peak brightness [1–3]. As a fourth-generation X-ray source, SHINE will provide cutting-edge experimental platforms for scientists across diverse fields worldwide. Ultra-intense lasers enable high-energy particle accelerators, taking advantage of the compactness, tunability, and high brightness of laser systems [4,5] to open new opportunities for multidisciplinary research including superheavy nuclei synthesis [6–8], quantum-mechanical processes [9], fundamental particles [10], and nuclear structure and photonuclear physics [11-13]. With its 100 PW laser at the Station of Extreme Light (SEL) [14,15], upgraded and constructed based on the existing Shanghai Superintense Ultrafast Laser Facility (SULF) of 10 PW and 1 PW, and the 8 GeV electron beam from the Superconducting Linear Accelerator (SLA) [16,17], various particle beams can be generated through laser-target interaction of the ultra-intense ultra-short laser (UIUSL) system, such as high-energy γ-rays, positron sources, and even heavy-ion beams.

For collisions between the UIUSL and high-energy electron beam [18,19], γ-rays are generated through nonlinear inverse Compton scattering (NICS), and electron-positron pairs are produced through the multiphoton Breit-Wheeler process (MBWP) via quantum electrodynamics (QED) effects when the optical laser field is sufficiently strong [20–22]. Several experiments have successfully obtained γ-ray beams through NICS: (1) at the Rutherford Appleton Laboratory (RAL), an electron beam accelerated by a laser of intensity 4×10^{19} W/cm^2 underwent NICS with a laser of intensity 8×10^{18} W/cm^2, generating a γ-ray beam with maximum energy 18 MeV and peak brilliance 1.8×10^{20} photons/(s $\cdot$ mm$^2 \cdot$ mrad$^2 \cdot$ 0.1%BW) [23]; (2) also at RAL, an electron beam accelerated by a laser of intensity 7.7×10^{18} W/cm^2 underwent NICS with a laser of intensity 1.3×10^{21} W/cm^2, generating γ-rays with critical energy of 30 MeV [24]. Earlier theories and simulations demonstrated that: (1) increasing the electron Lorentz factor and laser intensity could increase the energy of produced γ-rays; (2) enhanced stability of the electron beam might reduce the emittance of the γ-ray beam [25,26]; and (3) increasing laser intensity might also enhance the laser energy conversion efficiency to γ-rays and positrons [27].

Combining all these favorable factors, high-quality γ-ray and positron beams could be generated by the SEL 100 PW laser and SLA 8 GeV electron beam through NICS and MBWP processes at SHINE. Compared to GeV-level γ-rays produced by bremsstrahlung [28], NICS makes it possible to produce a first-class high-quality γ-ray source above the GeV level at SHINE, and significantly improve the energy of γ-ray sources at the nearby Shanghai Laser Electron Gamma Source (SLEGS) [29,30]. Motivated by these promising opportunities, the particle-in-cell (PIC) program SMILEI is employed to simulate the complete interaction between the UIUSL and high-energy electron beam, and the feasibility of this scheme is elucidated, which also fills the gap in research on γ-ray and positron beams. This article is organized as follows. In Section II, the key physical mechanisms and parameter settings of the simulations are highlighted. The simulation results, including the spatial distribution, energy spectrum, and spatial electric field distribution of particles, are presented in Section III. The beam parameters and applications are discussed in Section IV. The main findings are summarized in Section V.

II. MODELS AND SIMULATIONS

The SMILEI toolkit, a collaborative, open-source, user-friendly PIC code, has been applied to a wide range of physics studies from relativistic laser-plasma interactions to astrophysical plasmas [31]. Within all simulated grids, the motion of particles in the electromagnetic field satisfies Vlasov’ s equation and gradually forms a self-consistent dynamical system [32–34]. The mechanism of high-energy γ-ray production in collisions between the UIUSL and high-energy electron beam is the incoherent process of NICS. The dynamics of a single electron with charge -e and mass m could be determined by the Lorentz equation in an arbitrary external field, described by the covariant form of the Lorentz equation with the electromagnetic field tensor F^{ } in the form F^{ }p_ .

The Lorentz invariant quantum parameter for the electron is

$$\chi_e = \frac{\gamma_e}{E_s}\sqrt{(E + v \times B)^2 - (v \cdot E)^2}$$

and the Lorentz invariant quantum parameter for the photon at the time of photon emission is

$$\chi_\gamma = \frac{\gamma_\gamma}{E_s}\sqrt{(E + c \times B)^2 - (c \cdot E)^2}$$

where $\gamma e =$ _e/(m{ec}^{2}) and $\gamma\gamma =$ γ/(m_{ec}^{2}) are the normalized energies of the radiating particle and emitted photon, respectively; v and c are their respective velocities, c is the speed of light in vacuum. E and B denote the electric and magnetic fields, respectively; and E_s = m^{2}c^3/(e) 1.3 × 10^{18} V/m is the Schwinger field.

The MBWP is the process of high-energy photons decaying into an electron-positron pair in an intense electromagnetic field [35,36]. The strength of QED effects for electrons and positrons depends on the photon quantum parameter

$$\chi_\gamma = \frac{\gamma_\gamma}{E_s}\sqrt{E_\perp^2 + (c \times B)^2}$$

where E_ is the electric field orthogonal to the propagation direction of the photon.

The parameters adopted in the SMILEI simulation are based on SHINE, where the mono-energetic electron beam density is 3.2 × 10^{24} m^{-3} and the beam spot size is 10 × 10 m^2, derived from the appropriate rectangular reduction of the highly intensive electron beam distribution. The laser is set to be a Gaussian laser with wavelength $\lambda = 1$ m, focal spot size 5 m, full-width-at-half-maximum (FWHM) 15 fs, and peak intensity I = 10^{23} W/cm^2, which corresponds to a normalized laser amplitude of a_{cir} 190 for circularly polarized laser (denoted by CPL) and a_{lin} 269 for linearly polarized laser (denoted by LPL) [37-39]. The spatial size of the two-dimensional and three-velocity (2D3V) particle-in-cell (PIC) simulation is set to 300 × 100 m^2, with a spatial step size of 100 nm and a time step of 22 as. Each grid initially contains 16 electrons in the electron beam region. The electron beam moves straight from the center on the left towards the right, while the laser focusing on the electron beam travels from the center on the right towards the left.

The γ-ray is immediately emitted by collision of electrons and photons through the NICS mechanism [40,41], specifically using Monte Carlo simulation [42-44]. Almost simultaneously, the electron-positron pair is created by photons through the MBWP mechanism. The collision processes, as well as the colliding equations, are illustrated in Fig. 1 [Figure 1: see original paper], which includes NICS: e^- + mγ*{laser}* $\rightarrow \gamma + e^-$, *MBWP:* γ + $n\gamma${laser} $\rightarrow$ $e^+ + e^-$.

Fig. 1. (Color online) Schematic collision between the ultra-intense ultra-short laser (γ_{laser}) and the high-energy electron beam (e^-). The moving directions of particles are indicated by thick arrows.

III. RESULTS

At the time when the electrons interact with the laser and the number of positrons no longer increases, the results for particle production are shown under both CPL and LPL patterns, including the spatial distributions of produced particles, the energies of produced particles, and spatial electric field.

A. Particle spatial distribution

The spatial distributions for particles are plotted in Fig. 2 [Figure 2: see original paper]. For the CPL pattern, as shown in Fig. 2(a), (c) and (e), the spatial distributions of γ-rays, compared to electrons and positrons, are more dispersed in the Y direction. The spatial distributions of electrons and positrons almost overlap. The size of the beam center (black dashed box) almost equals the initial electron beam size. The central density of photons is greater than that of electrons, and positrons have the lowest central density.

For the LPL pattern, as shown in Fig. 2(b), (d) and (f), the spatial distribution resembles a "crown" adorned with a gem, with the beam center being the "gem" on the crown, which is quite different from the "meteor" pattern in the "rotating forward" CPL pattern. The γ-rays are also more dispersed in the Y direction compared to electrons and positrons. γ-rays have the highest central density, followed by electrons, and then positrons similarly. Compared to the CPL pattern, the particles in the LPL pattern markedly spread on the sides of the beam center in the vertical direction and have a higher particle density. Under both patterns, the same diffusion phenomena of particles occur in the Y direction close to the beam center, and the particles in the horizontal direction are distributed mostly to the left of the beam center, with a cluster of electrons at the "tail end" , which refers to the left end of the X axis and the center of the Y axis.

B. Particle energy

The energy spectra of produced particles are plotted in Fig. 3 [Figure 3: see original paper]. The energy spectrum of γ-rays decreases quickly in the range of Energy [0, 8] GeV. For the LPL pattern, more photons are produced in the lower energy range (Energy $<$ 0.9 GeV), while for the CPL pattern, more photons are produced in the higher energy range (Energy $\geq$ 0.9 GeV), with the maximum energies for both patterns approaching 8 GeV.

The electron energy broadens from the mono-energetic to the low-energy region, and the energy spectra of electrons and positrons both gradually increase to form peaks and then decrease with increasing energy. The peaks of the electron and positron distributions are both located at Energy = 0.2 GeV for the CPL pattern, and at Energy = 0.1 GeV for the LPL pattern, with more positrons and electrons produced compared to the LPL pattern at the peak positions. More electrons are produced in the LPL pattern than in the CPL when Energy < 0.5 GeV, while the opposite trend occurs when Energy ≥ 0.5 GeV. The number of positrons produced in the CPL pattern is similarly less than that produced in the LPL pattern when Energy < 1.1 GeV, while the trend reverses when Energy ≥ 1.1 GeV. Notably, the maximum energy of electrons still approaches 8 GeV, and the maximum energy of positrons is close to 7 GeV.

C. Space electric field

The electric field strength reflects the spatial and momentum evolution of charged particles at their positions. Figure 4 [Figure 4: see original paper] shows the electric field, offering a more detailed reference for interpreting particle beams. Charged particles exhibit greater stability in regions where the electric field remains stable. As shown in Fig. 4(a)-(f), the electric field reaches its maximum at the "tail end" of the particles, decreasing towards both sides of the Y axis and the right side of the X axis. For electrons and positrons, the electric field at the beam center is relatively low, enabling most particles to move forward collectively. Conversely, the electric field is higher at the "tail end" , causing particles at the rear to diverge outward. The electric field is apparently weaker in the CPL pattern compared to the LPL pattern.

As seen from Fig. 4(g), the electrons and positrons of the CPL pattern are subjected to an electric field force in the Z direction, while those of the LPL pattern are not subjected to any electric field force in the Z direction. This reveals that electrons and positrons at the "tail end" diverge in three dimensions in the CPL pattern, while they only diverge in the X and Y directions in the LPL pattern.

Fig. 2. (Color online) Particle spatial distributions at 700 fs of the SMILEI simulated collisions between 100 PW laser and 8 GeV electron beam based on the Station of Extreme Light (SEL) and Superconducting Linear Accelerator (SLA) in the Shanghai High Repetition Rate X-ray Free Electron Laser and Extreme Light Facility (SHINE). (a) and (b) are for γ-rays production under circularly polarized laser (CPL) and linearly polarized laser (LPL) patterns, respectively. (c) and (d) are for electrons production under CPL and LPL patterns, respectively. (e) and (f) are for positrons production under CPL and LPL patterns, respectively. Particle beam parameters are given in Section IV.

Fig. 3. (Color online) Particle energy spectrum at 700 fs of the SMILEI simulated collisions between 100 PW laser and 8 GeV electron beam based on the SEL and SLA in SHINE. CPL and LPL denote circularly polarized laser

and linearly polarized laser, respectively.

Fig. 4. (Color online) The spatial electric field distribution at 700 fs of the SMILEI simulated collisions between 100 PW laser and 8 GeV electron beam based on the SEL and SLA in SHINE. Panels (a), (c), and (e) denote γ-rays, electrons and positrons in the CPL pattern, respectively. Panels (b), (d), and (f) denote γ-rays, electrons and positrons in the LPL pattern, respectively. Panel (g) is for the electric field component distribution in the Z direction.

IV. DISCUSSION

To specifically discuss the characteristics of particle beams produced in the simulations, an area of X [190, 230] m and Y [45, 55] m is delimited for further estimation of the angular spectrum, particle beam parameters, experimental layout, and potential applications in scientific research.

A. Angular spectrum

For convenience, __y = arctan(p__y/p__x) and __z = arctan(p__z/p__x) are defined. The angular spectra of particles in the selected beam region are plotted in Fig. 5 [Figure 5: see original paper], which shows that the __y angular spectra for different particles in the CPL pattern are obviously narrower than those in the LPL pattern, with almost equal peak values (__y 0). Among the three particle types, the __y angular spectrum of γ-rays shows the widest distribution with the highest peak values (about 2.4$×10^{10}$ for CPL and 7.7$×10^{10}$ for LPL). Electrons show a narrower angular spectrum with lower peak values around 1.2×10^9 for CPL and 6.8$×10^{8}$ for LPL. Positrons display the narrowest __y angular spectrum with the lowest peak value (approximately 2.0×10^8 for CPL and 2.6×10^8 for LPL), closely resembling the __y angular spectrum and peak value of electrons.

The __z angular spectrum of different particles in the CPL pattern is similar to their corresponding __y angular spectrum, whereas the widths of the __z angular spectrum for particles in the CPL pattern are greater than that of the __y angular spectrum for corresponding particles, with peaks of the __z angular spectrum approximately at 9.5×10^{10} for γ-ray beam, 1.2×10^9 for electron beam, and 1.8×10^8 for positron beam. Notably, for all particles in the LPL pattern, they are focused on __z = 0, owing to the absence of electric field in the Z direction. Particles in the CPL pattern display a significantly broader __z angular spectrum compared to those in the LPL pattern. These discrepancies could be attributed to limitations in the 2D simulation, which makes it difficult to select the effective region in the Z direction.

B. Particle beams parameters

The main parameters for the particle beams from simulated results—namely beam brilliance, beam emittance, and beam flux—are further discussed. The particle beam brilliance is given by Eq. (7),

$$L = \frac{N}{T \times D^2 \times \theta^2}$$

where N is the number of particles when the 2D area is extended to 3D space, T is approximately 30 fs, D = 10 m, and = a_0/ *{e^-} (Lorentz factor* γ{e^-} 1.57×10^4) is 12 mrad and 17 mrad for the CPL and LPL patterns, respectively [23]. The particle beam emittance in 2D space is described by

$$\epsilon = \sqrt{\langle y^2 \rangle \langle p_y^2 \rangle - \langle y p_y \rangle^2}$$

The peak flux of particle beam is defined as F = N/T. The equation for energy conversion efficiency is = E_p/E_{le}, where E_p is the total energy of the particle and E_{le} is the sum of the corresponding laser and initial electron energies.

For comparison, the 10 PW and 1 PW lasers at the SULF facility are also simulated, which collide with the same electron beam to yield particle beams. The 10 PW and 1 PW laser intensities are 10^{21} W/cm^2 and 10^{20} W/cm^2, respectively, with focal spot sizes of 5.5 m and 40 m, and FWHMs both of 30 fs [45,46]. In Fig. 6 [Figure 6: see original paper], the simulated particle beam brilliance spectrum for the 1 PW and 10 PW lasers in SULF, as well as the 100 PW laser in SHINE on the high-energy electron beam and experimental cross-sections of particles [47–49] are plotted. The remarkable differences between the simulated results are that fewer positrons can be produced with the SULF 10 PW laser, and no positrons can be yielded with the SULF 1 PW laser. Note that the trends of the energy-brilliance for beam particles are similar to the trends of the energy spectra for all particles in the SEL 100 PW laser. Although in different laser polarization states and with different numbers of particles in the beam region, the peak energy of electrons and positrons in the CPL pattern is still higher than those in the LPL pattern. The maximum value of beam brilliance in the CPL pattern is slightly lower than that in the LPL pattern. In accordance with the beam brilliance of SEL 100 PW, SULF 10 PW and 1 PW lasers, the results clearly demonstrate that more intense ultra-short lasers produce more γ-rays by colliding with electron beams, and also produce more positrons.

Table 1 presents the parameters of particle beams simulated by SMILEI for collisions between SEL 100 PW and SLA 8 GeV electron beam according to Fig. 6. The γ-ray beam brilliance in the CPL pattern (up to 1.09×10^{27} photons/(s $\cdot$ mm^2 $\cdot$ mrad^2)) is higher than that in the LPL pattern, and the positron beam brilliance in the LPL pattern (up to 4.93×10^{24} positrons/(s $\cdot$ mm^2 $\cdot$ mrad^2)) is higher than that in the CPL pattern. Interestingly, the beam emittance is around 0.1 mm $\cdot$ mrad in the CPL pattern, which is much smaller than 0.2 mm $\cdot$ mrad in the LPL pattern. Notably, the peak flux of γ-rays reaches up to 10^{25} photons/s, which is much higher than existing γ-ray sources [50], for example,

10^{6-9} photons/s in HIγS and 10^{5-10} photons/s in SLEGS. The high γ-ray flux results not only from the ultra-short pulse duration, but also from the fact that the γ-ray flux of existing sources is usually the average flux.

In the CPL pattern, γ-rays are the most abundant in the beam region, followed by electrons, with positrons being the least numerous. The electron beam brilliance is 1.52×10^{25} electrons/(s $\cdot$ mm^2 $\cdot$ mrad^2), and positron beam brilliance is 3.97×10^{24} positrons/(s $\cdot$ mm^2 $\cdot$ mrad^2). Similarly, the γ-ray energy conversion efficiency of 4.47% is the maximum, and the energy conversion efficiencies of electrons and positrons are 0.18% and 0.05%, respectively. The γ-rays and electrons have the highest energy in the beam region (up to 8 GeV), while the maximum particle energy of positron beams is approximately 7 GeV. The average particle energy of electron and positron beams, which is around 0.6 GeV, is higher than that of γ-ray beam (0.2 GeV).

In the LPL pattern, the beam brilliance, energy conversion efficiency, maximum particle energy, and average particle energy have the same numerical order in terms of the three particle types: γ-rays, electrons and positrons. The γ-ray and electron beam brilliances are 8.89×10^{26} photons/(s $\cdot$ mm^2 $\cdot$ mrad^2) and 1.05×10^{25} electrons/(s $\cdot$ mm^2 $\cdot$ mrad^2), respectively. The energy conversion efficiency of γ-rays is 5.96%, which is marginally superior to the 2% given by the all-optical scheme for laser energy conversion into γ-rays in 2012 [51]. The energy conversion efficiencies of electrons and positrons are 0.19% and 0.09%, respectively. The maximum particle energies are similar to those in the CPL pattern. The average particle energy of electron and positron beams is about 0.4 GeV, and the average particle energy of γ-ray beam is about 0.2 GeV.

Although the maximum energy of γ-rays approaches the initial electron energy during the collision process, the majority of γ-rays still have lower energy. At the same time, most of the positrons have higher energy. In general, the energy conversion efficiency of particles in the CPL pattern is lower than that in the LPL pattern, while the maximum particle energy in the CPL pattern is nearly equal to that in the LPL pattern, and the average particle energy in the CPL pattern is higher than that in the LPL pattern. These conflicting results could be related to the fact that more positrons are generated with lower energy and greater spatial emittance in the beam region in the LPL pattern. It is suggested that, to generate γ-rays and electrons, the CPL pattern demonstrates superior beam quality, whereas to generate positrons, the LPL pattern may achieve higher beam quality in SHINE.

C. Facility layout and applications

The simulations in this work provide an alternative way to produce high-quality γ-ray and positron beams in all-optical scheme designations [52–54], which use the UIUSL to generate a higher-energy electron beam that then collides with another UIUSL. The simulated results aim to assess the feasibility and advantages of an electron-laser colliding γ-ray source and positron beam facility, which provides new opportunities for high-energy photonuclear reactions and positron-related physics within the aforementioned energy ranges. Examples of different (γ, π^0), (γ, abs) and (γ, f) reactions within the high-energy scopes are also plotted in Fig. 6, which could enhance comprehensive understanding of nuclear structures such as form factors, polarization, and resonances [55], and the high-brilliance and high-flux particle beams may partly advance nuclear reaction yields. Particle energies follow a continuous spectrum defined by the surrounding temperature in the high-temperature, high-density plasma of extreme astrophysical environments, including γ-ray bursts in active galactic nuclei, pulsars, stellar interiors, supernovae, neutron star mergers, and so on. Utilizing a beam with a continuous energy spectrum could more effectively simulate the overall effects of particles in real astrophysical environments, such as the integrated reaction rates under a continuous γ-ray spectrum, which are crucial for experimentally verifying model parameters in the evolution of nuclear celestial bodies and may reveal new phenomena in astrophysics. The potential high-quality γ-ray beams at SHINE would significantly promote nuclear reaction research, as well as investigations of strange phenomena in nuclear physics and nuclear astrophysics.

The concept design for a possible colliding station based on the SEL 100 PW laser and SLA 8 GeV electron beam in SHINE is shown in Fig. 7 [Figure 7: see original paper]. First, the spatial distributions of the three types of particles overlap as demonstrated by the simulated results. Then, it is possible to achieve beam separation by placing deflecting magnets around the beam region [22,56,57]. Finally, neutral γ-rays would still propagate in the positive direction along the X axis, while electrons and positrons would propagate in opposite directions along the Y axis [21,53,58]. Furthermore, the maximum energy of γ-rays varies with momentum angle __y in the beam region at 700 fs, especially when the energy exceeds 100 MeV. γ-rays near the 0-degree momentum angle, with energy below 100 MeV, have the highest proportion. The ultra-intense γ-rays are ideal for studying photonuclear reactions of short-lived unstable nuclides with high cross-sections and minimal rare nuclide target material [59–61], and γ-ray-assisted multiphoton fusion processes [62]. Therefore, the potential applications of γ-rays in different energy regions are as follows:

- High-energy γ-rays ($\geq$ 140 MeV) could be used to research pion photoproduction on the nucleon [63–65], and determine more accurate resonance coupling constants through additional experimental measurements of the nucleon resonance spectrum [66,67].
- Medium-energy γ-rays ($\geq$ 100 MeV) could be used to study photonuclear spallation reactions, improving the photonuclear reaction database [13,68,69].
- Low-energy γ-rays (1–30 MeV) could be used to investigate laboratory astrophysics [70–72], and the enhanced low-energy γ-rays also provide a strong platform for medical isotope production [73,74], phototransmutation [75–77], and activation experiments [78,79] through photonuclear reactions [80–82].

In concrete terms, these high-quality particle beams may have practical multidisciplinary applications:

- **Unique and complementary photonuclear reactions and related applications:** The different cross-sections of photonuclear reactions induced by high-energy γ-rays allow for differentiation between stable and unstable isotopes in samples using γ-ray spectroscopy [50,83,84], production of radioactive isotopes for medical applications [73,85], and investigation of reaction mechanisms in nuclear spallation reactions [13]. These researches could potentially be performed within γ-ray energy ranging from hundreds of MeV to 8 GeV. The strong penetrating power of γ-rays can be applied for non-destructive testing of large engineering samples, and their high brilliance can also serve as a microscope for studying material lattice dynamics [86–88].
- **Positrons and related applications:** As one type of antimatter particles, positrons have applications in particle physics research [89], solid-state physics such as diagnosing complex structures of Fermi surfaces [90], and Positron Emission Tomography (PET) for material sciences [91].
- **Nonlinear strong-field QED verification:** Experiments for precision measurements of high-energy heavy element reaction events can be conducted to verify predictions of nonlinear QED effects using these three types of particles [42,92,93].

However, several questions still remain in both techniques and theory. One is how to achieve collisions by synchronizing the electron beam and laser within a few femtoseconds and microns [94–96], which requires extremely high initial beam quality and technical precision [28,97,98]. Another is that the maximum energy of the three types of particles may not exceed the maximum energy of the initial electron beam, which requires increasing the electron beam energy of the accelerator to obtain higher γ-ray and positron beam energies. The third is that the aforementioned applications, such as those involving photonuclear reactions, necessitate the development of detectors with higher sensitivity and the exploration of theoretical models under extreme conditions.

V. CONCLUSION

Comprehensive simulations have been performed on particle production in collisions between the SEL 100 PW laser and SLA 8 GeV electron beam at SHINE using the PIC program SMILEI. Most of the γ-rays and electron-positron pairs generated by NICS and MBWP are found to be localized in the beam center, where the beam center size matches that of the initial electron pulse. The majority of γ-rays are distributed in the lower energy range (Energy < 0.9 GeV), and the generated electrons and positrons are concentrated at Energy $= 0.2$ GeV for CPL and Energy $= 0.1$ GeV for LPL. Electrons and positrons move forward in the beam center, whereas those in the "tail end" spread out in 3D space for the CPL pattern and spread out in the X and Y directions for the LPL pattern. Within the selected beam region, the angles of particle momentum are clustered around 0 degrees, and the beam brilliance rises with increasing laser intensity. The beam brilliance of the γ-rays, with a maximum energy of up to 8 GeV, reaches 10^{27} photons/$(\mathrm{s} \cdot \mathrm{mm}^2 \cdot \mathrm{mrad}^2)$. The beam emittance is approximately 0.1 mm $\cdot$ mrad in the CPL pattern, and its energy conversion efficiency is up to 5.96% in the LPL pattern. The maximum energy of positrons reaches 7 GeV, with a beam brilliance of up to 4×10^{24} positrons/$(\mathrm{s} \cdot \mathrm{mm}^2 \cdot \mathrm{mrad}^2)$, a beam emittance of approximately 0.1 mm $\cdot$ mrad in the CPL pattern, and an energy conversion efficiency of 0.09% in the LPL pattern.

The high brilliance, high energy, and low emittance are the advantages of the γ-ray, positron, and electron beams generated in the simulated collisions. The γ-ray beam brilliance is higher and the beam emittance is lower in the CPL pattern than in the LPL pattern. The positron beam brilliance is higher and the particle energy conversion efficiency is larger in the LPL pattern than in the CPL pattern. The insights gained from these results may inspire us to choose distinct laser polarization patterns, various energy ranges achieved through moderating materials, and diverse particle beams guided by magnets to achieve specific experimental research goals, such as studying photonuclear reactions and verifying strong-field QED theory.

Besides the quantitative and comprehensive assessment of top-quality γ-ray and positron beams with the most intense laser, this work explores the feasibility of the facility design scheme. Multiple frontier applications have been presented with these γ-ray and positron beams, including γ-ray microscopy in material science and engineering, γ-ray spectrum diagnostics of radionuclides, PET for advanced nuclear analysis technology, and so on. Moreover, if the particle beams, and even the electrons of the SLA [99], can be polarized [100–102] and vortexed [103], they will have significant potential to enhance the research dimension of plasma physics and advance studies in nuclear physics and astrophysics [104].

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DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding authors upon reasonable request.

DECLARATIONS

Conflict of interest: Chun-Wang Ma and Xi-Guang Cao are editorial board members for Nuclear Science and Techniques and were not involved in the editorial review or the decision to publish this article. All authors declare that there is no conflict of interest.

Note: Figure translations are in progress. See original paper for figures.