# GeV-level $\gamma$-ray and positron beams produced by collisions of multi-PW laser on high-energy electron beam

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## Abstract

Based on collisions between the 100 PW laser and 8 GeV superconducting linear accelerator under construction in Shanghai High Repetition Rate X-ray Free Electron Laser and Extreme Light Facility, the construction of GeV-level $\gamma$-ray as well as positron beams was proposed according to particle-in-cell simulations. Key processes were considered, involving the nonlinear inverse Compton scattering for $\gamma$-ray generation and the multiphoton Breit-Wheeler process for electron-positron pair production. Regardless of laser polarization, the simulations indicate that $\gamma$-ray beams achieved energies up to 8 GeV, brilliance of approximately 1027 photons/(s · mm2 · mrad2), and emittance as low as 0.1 mm · mrad, whereas positron beams attained energies up to 7 GeV, brilliance of approximately 4\$×\$1024 positrons/(s · mm2 · mrad2), and emittance as low as 0.1 mm · mrad. Various applications could benefit from the possible high-energy $\gamma$-ray and positron beams, which may potentially be built in SHINE, including validation of the fundamental physics of strong-field quantum electrodynamics theory, nuclear physics, nuclear astrophysics, and imaging.

## Full Text

## Preamble

GeV-level $\gamma$-ray and positron beams produced by collisions of multi-PW laser on high-energy electron beam∗ Wan-Qing Su,1, 2, 3 Chun-Wang Ma,1, 4, † Xi-Guang Cao,2, 3, 5, ‡ Guo-Qiang Zhang,2, 3, 5 and Yu-Ting Wang1 1School of Physics, Henan Normal University, Xinxiang 453007, China 2Shanghai Advanced Research Institute, Chinese Academy of Sciences, Shanghai 201210, China 3Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai 201800, China 4Institute of Nuclear Science and Technology, Henan

Academy of Sciences, Zhengzhou 450046, China 5University of Chinese Academy of Sciences, Beijing 101408, China Based on collisions between the 100 PW laser and 8 GeV superconducting linear accelerator under con- struction in Shanghai High Repetition Rate X-ray Free Electron Laser and Extreme Light Facility, the con- struction of GeV-level $\gamma$-ray as well as positron beams was proposed according to particle-in-cell simulations.

Key processes were considered, involving the nonlinear inverse Compton scattering for $\gamma$-ray generation and the multiphoton Breit-Wheeler process for electron-positron pair production. Regardless of laser polarization, the simulations indicate that $\gamma$-ray beams achieved energies up to 8 GeV, brilliance of approximately 1027 photons/(s ·mm2 ·mrad2), and emittance as low as 0.1 mm · mrad, whereas positron beams attained energies up to 7 GeV, brilliance of approximately 4 × 1024 positrons/(s ·mm2 ·mrad2), and emittance as low as 0.1 mm ·mrad. Various applications could benefit from the possible high-energy $\gamma$-ray and positron beams, which may potentially be built in SHINE, including validation of the fundamental physics of strong-field quantum electrodynamics theory, nuclear physics, nuclear astrophysics, and imaging.

Keywords: $\gamma$-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 offer a pho- ton beam with energy spanning from 0.4 to 25 keV, lever- aging its MHz-level high repetition rate and fs-level ultrashort pulse, to achieve exceptionally high average bright- ness 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. The ultra-intense laser induces high-energy particle accelerators, taking advantage of compactness, tunability and high bright- ness of laser system [4, 5] to open new opportunities for mul- tidisciplinary research, including superheavy nuclei synthesis [6–8], quantum-mechanical processes [9], fundamental par- ticles [10], nuclear structure, and photonuclear physics [11–13]. With its 100 PW laser of the Station of Extreme Light (SEL) [14, 15], which is upgraded and constructed based on the existing Shanghai Superintense Ultrafast Laser Fa- cility (SULF) with 10 PW and 1 PW, and the 8 GeV elec- tron beam of the Superconducting Linear Accelerator (SLA) [16, 17], various particle beams can be generated by laser target shooting of the ultra-intense ultra-short laser (UIUSL) system, such as the high-energy $\gamma$-rays, positron sources, and ∗ This work is supported by the National Key Research and Develop- ment Program of China (Nos. 2022YFA1602404 and 2022YFA1602402), the National Natural Science Foundation of China (Nos. 12475134, 11975210, 12235003, and U1832129), the Strategic Priority Research Pro- gram of the CAS (No. XDB34030000), the Youth Innovation Promo- tion Association CAS (No. 2017309), and Natural

Science Foundation of Henan Province (No. 242300421048). † Corresponding author, machunwang@126.com ‡ Corresponding author, caoxg@sari.ac.cn even heavy-ion beams. $\gamma$-rays offer vast promising appli- cations in different energy regions, for example, low-energy $\gamma$-rays (1-30 MeV) could be used to investigate the labora- tory astrophysics [18–20], and the enhanced low-energy $\gamma$-rays also provide a strong platform for medical isotope pro- duction [21, 22], photo-transmutation [23–25], and activation experiments [26, 27] through photonuclear reactions [28–30]; medium-energy $\gamma$-rays (  100 MeV) could be used to study photonuclear spallation reactions, improving the pho- tonuclear reaction database [13, 31, 32]; high-energy $\gamma$-rays (  140 MeV) could be used to research pion photoproduction on the nucleon [33–35], and determine more accurate resonance coupling constants through more experimental mea- surements of the nucleon resonance spectrum [36, 37]. The positron, as an antimatter particle, also has cutting-edge ap- plications in the research of particle physics [38], Positron Emission Tomography (PET) for material sciences [39], and solid-state physics, such as diagnosing complex structures of Fermi surfaces [40].

For collisions between the UIUSL and high-energy elec- tron beam [41, 42], $\gamma$-rays are generated through nonlin- ear inverse Compton scattering (NICS), and electron-positron pairs are yielded through the multiphoton Breit-Wheeler process (MBWP) of the quantum electrodynamics (QED) ef- fects when the optical laser field is sufficiently intense [43–45]. Several experiments have successfully obtained $\gamma$-ray beams through NICS: (1) an electron beam accelerated by a laser of intensity 4 × 1019 W/cm2 undergoes NICS with a laser of intensity 8 × 1018 W/cm2 at the Rutherford Apple- ton Laboratory (RAL), generating a $\gamma$-ray beam with a max- imum energy of 18 MeV and peak brilliance of 1.8 × 1020 photons/(s ·mm2 ·mrad2 ·0.1%BW) [46]; (2) an electron beam accelerated by a laser of intensity 7.7 × 1018 W/cm2 also undergoes NICS with a laser of intensity 1.3 × 1021 W/cm2 at the RAL, generating a $\gamma$-ray with a critical energy of 30 MeV [47]. Earlier theories and simulations demon- strated that (1) an increase in the electron Lorentz factor and laser intensity can increase the energy of $\gamma$-ray produced; (2) the enhanced stability of electron beam might reduce the emittance of the $\gamma$-ray beam [48, 49]; and (3) an increase in the laser intensity might also enhance the laser energy con- version efficiency to $\gamma$-rays and positrons [50].

Considering all the favorable factors mentioned above, high-quality $\gamma$-ray and positron beams can be generated by an SEL 100 PW laser and an SLA 8 GeV electron beam through the NICS and MBWP processes in SHINE. In comparison with the GeV-level $\gamma$-rays produced by bremsstrahlung [51], the NICS makes it possible to produce a first-class high- quality $\gamma$-ray source above the GeV-level in SHINE and sig- nificantly improve the energy of $\gamma$-ray source at the nearby Shanghai Laser Electron Gamma Source (SLEGS) [52]. The upcoming $\gamma$-ray, positron, and electron beams may have prac- tical multidisciplinary applications. One unique and comple- mentary application is photonuclear reactions and related ap- plications of $\gamma$-rays: the different cross-sections of photonuclear reactions induced by high-energy $\gamma$-rays allow for the differentiation between stable and unstable isotopes in sam- ples using $\gamma$-ray spectroscopy [53-55], radioactive isotope production for medical applications [21, 56], and reaction mechanism of nuclear spallation reactions [13]. These studies have the potential to be performed within $\gamma$-ray energies rang- ing from hundreds of MeV to 8 GeV. The strong penetrating power of $\gamma$-rays can be applied to the non-destructive testing of large engineering samples, and the high-brilliance $\gamma$-ray beam can also serve as a microscope for the study of mate- rial lattice dynamics [57, 58]. Another application is nonlin- ear strong-field QED verification: experiments for precision measurements of high-energy heavy element reaction events can be conducted to verify the predictions of nonlinear QED effects using these three types of particles [59-61]. Motivated by these promising opportunities, the particle-in-cell (PIC) program SMILEI was employed to simulate the entire processes between the UIUSL and high-energy electron beam, and the feasibility of this scheme was elucidated, which also fulfilled the gap between the $\gamma$-ray and positron beam re- search. This article is organized as follows. In Sect. II, the key physical mechanisms and parameter settings of the simu- lations are highlighted. The simulation results, including the spatial distribution, energy spectrum, and spatial electric field distribution of the particles, are presented in Sect. III. The beam parameters and specific applications of the particles are discussed in Sect. IV. The main findings are summarized in Sect. V.

II. MODELS AND SIMULATIONS The SMILEI toolkit, which is a collaborative, open-source, and user-friendly PIC code, has been applied to a wide range of physics studies, from relativistic laser-plasma interactions to astrophysical plasmas [62]. Within all the simulated grids, the motion of particles in the electromagnetic field satisfies Vlasov’ s equation and gradually forms a self-consistent dy- namical system [63-65]. The mechanism of high-energy $\gamma$- ray production in collisions between the UIUSL and high- energy electron beam is an incoherent process known as 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, which is described by the covariant form of the Lorentz equation with the electromagnetic field tensor F μ$\nu$ in the form of F μ$\nu$p$\nu$.

The Lorentz invariant quantum parameter for the electron is (cid:115) (cid:12) (cid:12) (cid:12) (cid:12) (cid:12) (cid:12) (cid:12) (cid:12) (E + v × B)2 − (v · E)2 and the Lorentz invariant quantum parameter for the photon at the time of photon emission is denoted as (cid:115) (E + c × B)2 − (c · E)2 where $\gamma$e = $\epsilon$e/ (cid:0)mec2(cid:1) and $\gamma\gamma$ = $\epsilon\gamma$/ (cid:0)mec2(cid:1) are the nor- malized 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 field and magnetic field, respectively; and Es = m2c3/ ( e)   1.3 × 1018 V/m is the Schwinger field. The MBWP is the process in which high-energy photons decay into an electron- positron pair in an intense electromagnetic field [66, 67]. The strength of the QED effects for electron and positron depends on the photon quantum parameter.

The parameters adopted in the SMILEI simulation are based on the SHINE, where the monoenergetic electron beam density is 3.2 × 1024 /m3, the beam charge is 200 pC, the full- width-at-half-maximum (FWHM) is approximately 66 fs, and the beam spot size is 10 × 10 µm2, derived from the appro- priate rectangular reduction of the highly intensive electron beam distribution. The laser is set to be a Gaussian laser with a wavelength $\lambda = 1$ µm, a focal spot size of 5 µm, a FWHM of 15 fs, and a peak intensity I = 1023 W/cm2, which corresponds to a normalized laser amplitude of acir 190 for cir- cularly polarized laser (denoted by CPL) and alin 269 for linearly polarized laser (denoted by LPL) [68–70]. The spa- tial size of the two-dimensional and three-velocity (2D3V) particle-in-cell (PIC) simulation is set to be 300 µm × 100 µm, with a spatial step size of 100 nm and a time step of 22 as. Each grid initially contained 16 electrons in the elec- tron beam region. The electron beam moved straight from the center on the left towards the right, whereas the laser fo- cused on the electron beam traveled from the center on the right towards the left. The $\gamma$-rays are immediately emitted by the collision of electrons and photons through the NICS mechanism [71, 72], specifically, via the Monte Carlo simu- lation [59, 73, 74]. Almost simultaneously, electron-positron pairs are 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− + m $\gamma$laser → $\gamma$ + e−, MBWP : $\gamma$ + n $\gamma$laser → e+ + e−.

Fig. 1. (Color online) Schematic collision between the ultra-intense ultra-short laser ($\gamma$laser) and the high-energy electron beam (e−).

The moving directions of particles are indicated by thick arrows.

III. RESULTS When the electrons interact with the laser and the num- ber of positrons no longer increases, the results for particles production are shown under both the CPL and LPL patterns, including the spatial distributions of the produced particles, the energies of the produced particles, and the space electric field.

A. Particle spatial distribution The spatial distributions of the 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 $\gamma$-rays, compared with those of electrons and positrons, are more dispersed in the Y direc- tion. The spatial distributions of the electrons and positrons almost overlap. The central sizes of the three generated par- ticle beams are almost equal to the initial electron beam size.

The central density of $\gamma$-rays 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 distribu- tion of particles resembles a “crown” adorned with a “gem” , which is the beam center (black dashed box), and it is quite different from the “meteor” pattern in the “rotating forward” CPL pattern. The $\gamma$-rays are also more dispersed in the Y di- rection than the electrons and positrons. $\gamma$-rays have the high- est central density, followed by electrons, and then positrons, the latter being similar to the electrons. Compared with the CPL pattern, the particles in the LPL pattern are 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 direc- tion close to the beam center, and the particles in the horizon- tal direction are distributed mostly to the left of the beam cen- ter, 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.

Fig. 2. (Color online) Particle spatial distributions at 700 fs of the SMILEI simulated collisions between 100 PW laser and 8 GeV elec- tron beam based on the Station of Extreme Light (SEL) and Super- conducting Linear Accelerator (SLA) in the Shanghai High Repe- tition Rate X-ray Free Electron Laser and Extreme Light Facility (SHINE). (a) and (b) are for $\gamma$-rays production under circularly po- larized laser (CPL) and linearly polarized laser (LPL) patterns, re- spectively. (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 Sect. IV.

B. Particle energy The energy spectra of produced particles are plotted in Fig. 3 [Figure 3: see original paper]. The energy spectrum of $\gamma$-rays decreases rapidly in the range of Ek   [0, 8] GeV. For the LPL pattern, more pho- tons are produced in the lower energy range (Ek $<$ 0.9 GeV), whereas for the CPL pattern, more photons are produced in the higher energy range (Ek   0.9 GeV), with the maximum energies for both patterns approaching 8 GeV. The electron energy broadens from the mono-energy to the low-energy re- gion, and the energy spectra of electrons and positrons both gradually increase to form peaks and then decrease with the increasing energy. The peaks of the electron and positron dis- tributions are both located at Ek = 0.2 GeV for the CPL pat- tern, and the peaks of the electron and positron distributions are both located at Ek = 0.1 GeV for the LPL pattern, and more positrons and electrons are produced compared to the LPL pattern at the peak positions. More electrons are pro- duced in the LPL pattern than in the CPL when Ek $<$ 0.5 GeV, whereas the opposite trend occurs when Ek   0.5 GeV.

The number of positrons produced in the CPL pattern is sim- ilarly less than that produced in the LPL pattern when Ek $<$

## 1.1 GeV, whereas the trend reverses when Ek   1.1 GeV.

Notably, the maximum energy of electrons still approaches 8 GeV, and the maximum energy of positrons is close to 7 GeV.

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

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, which offers a more detailed refer- ence 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 to- wards both sides of the Y axis and the right side of the X axis.

For electrons and positrons, the electric field at the beam cen- ter 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 than in 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 di- rection, whereas these of the LPL pattern are not subjected to any electric field force in the Z direction. It was revealed that the electrons and positrons at the "tail end" diverge in three dimensions in the CPL pattern, whereas they only diverge in the X and Y directions in the LPL pattern.

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 the $\gamma$-rays, electrons, and positrons in the CPL pattern, respectively. The panels (b), (d), and (f) denote $\gamma$-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] µm and Y [45, 55] µm is delimited for further estimation of the angular spectrum, particle beams parameters, experimen- tal layout and specific applications in scientific research.

A. Angular spectrum For convenience, $\theta$y = arctan(py/px) and $\theta$z = arctan(pz/px) are defined to portray the particle beams. The angular spectra of the particles in the selected beam region are plotted in Fig. 5 [Figure 5: see original paper], which shows that the $\theta$y angular spec- tra for different particles in the CPL pattern are consider- ably narrower than those in the LPL pattern, with peak val- ues for the same particles almost equal at $\theta$y 0. Among the three particles, the $\theta$y angular spectrum of $\gamma$-rays shows the widest distribution with the highest peak values (approxi- mately 2.4 × 1010 for CPL and 7.7 × 1010 for LPL). Electrons exhibit a narrower angular spectrum with lower peak values (approximately 1.2 × 109 for CPL and 6.8 × 108 for LPL).

Positrons display the narrowest $\theta$y angular spectrum with the lowest peak value (approximately 2.0 × 108 for CPL and 2.6 × 108 for LPL), closely resembling the $\theta$y angular spec- trum and peak value of electrons. The $\theta$z angular spectrum of different particles in the CPL pattern is similar to their cor- responding $\theta$y angular spectrum in the CPL pattern, whereas the widths of the $\theta$z angular spectrum for particles in the CPL pattern are greater than those of the $\theta$y angular spectrum for the corresponding particles in the CPL pattern, with the peaks of the $\theta$z angular spectrum approximately at 9.5\$×\$1010 for the $\gamma$-ray beam, 1.2\$×109*fortheelectronbeam, and*1.8×\$108 for the positron beam. Notably, for all particles in the LPL pat- tern, they are focused on $\theta$z = 0, owing to the absence of an electric field in the Z direction. Particles in the CPL pattern display a significantly broader $\theta$z angular spectrum than those in the LPL pattern. These discrepancies could be attributed to limitations in the 2D simulation, which makes it difficulty to select the effective region in the Z director.

Fig. 5. (Color online) The angular spectrum of particle momentum ($\theta$y = arctan(py/px) and $\theta$z = arctan(pz/px)) in the beam re- gion at 700 fs simulated by SMILEI for collision between circularly polarized (CPL) or linearly polarized (LPL) SEL 100 PW laser and SLA 8 GeV electron beam.

B. Particle beams parameters The main parameters for the particle beams in the simu- lated results, namely, beam brilliance, beam emittance, and beam flux, are further discussed. The particle beam brilliance is given by Eq. (6), T × D2 × \$ \$2 , where N is the number of particles when the 2D area is extended to the 3D space, T is approximately 30 fs, D = 10 µm, and $\theta$ = a0/$\gamma$e− (Lorentz factor $\gamma$e− 1.57 × 104) is 12 mrad and 17 mrad for the CPL and LPL patterns, re- spectively [46]. The particle beam emittance in 2D space is described by, (cid:118) (cid:117) (cid:117) (cid:116) y2 (cid:19)2(cid:43) (cid:42)(cid:18) py (cid:68) (cid:69)2 The peak flux of the particle beam is defined as F = N/T .

The energy conversion efficiency is $\eta$ = Ep/Ele, where Ep is the total energy of the particle and Ele is the sum of the energies of the corresponding laser and initial electrons, re- spectively.

For comparison, the 10 PW and 1 PW lasers at the SULF facility were also simulated, which collided with the same electron beam to yield particle beams. The SULF 10 PW and

## 1 PW laser intensities were 1021 W/cm2 and 1020 W/cm2,

respectively, with focal spot sizes of 5.5 µm and 40 µm, re- spectively, and FWHMs of 30 fs [75, 76]. In Fig. 6 [Figure 6: see original paper], the simulated particle beam brilliance spectra 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 [77-79] are plotted. The remarkable differences between the simulated results are that fewer positrons can be produced in the SULF 10 PW laser and that positrons can- not be produced in the SULF 1 PW laser. It should be noted 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 polariza- tion states and the number of particles in the beam region, the peak energy of electrons and positrons in the CPL pattern is still higher than that 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 bril- liance of the SEL 100 PW, SULF 10 PW, and 1 PW lasers, the phenomena clearly demonstrate that a more intense ultra- short laser produces more $\gamma$-rays when colliding with an elec- tron beam and that more positrons are also produced.

Table 1 presents the parameters of particle beams simu- lated by SMILEI for collisions between the SEL 100 PW and SLA 8 GeV electron beam according to Fig. 6. The $\gamma$- ray beam brilliance in the CPL pattern (up to 1.09 × 1027 photons/(s · mm2 · mrad2)) is higher than that in the LPL pat- tern, and the positron beam brilliance in the LPL pattern (up to 4.93 × 1024 positrons/(s · mm2 · mrad2)) is higher than Interestingly, the beam emittance that in the CPL pattern.

Fig. 6. (Color online) The particle beam brilliance spectrum (denoted by the left Y axis) at 700 fs simulated by SMILEI for collision between the CPL and LPL patterns of SEL 100 PW, Shanghai Superintense Ultrafast Laser Facility (SULF) 10 PW or 1 PW lasers and the SLA 8 GeV electron beam, respectively. The experimental data for photonuclear reaction cross-sections are denoted by the right Y axis [77–79].

Table 1. Particle beam parameters simulated by SMILEI for collision between circularly polarized (CPL) or linearly polarized (LPL) SEL 100 PW laser and SLA 8 GeV electron beam. The laser polarization (P), particle type (T), beam brilliance (L), average particle energy (Eavg), maximum particle energy (Emax), emittance ($\epsilon$), peak flux (F ), and energy conversion efficiency ($\eta$) are given. $\gamma$-ray Electron Positron $\gamma$-ray Electron Positron L (particles/(s · mm2 · mrad2)) Eavg (GeV) Emax (GeV) 1.09 × 1027 1.52 × 1025 3.97 × 1024 8.89 × 1026 1.05 × 1025 4.93 × 1024 $\epsilon$ (mm · mrad) F (particles/s) $\eta$ (%) 1.82 × 1025 2.48 × 1023 6.57 × 1022 4.26 × 1025 4.49 × 1023 2.11 × 1023 is approximately 0.1 mm · mrad in the CPL pattern, which is considerably smaller than 0.2 mm · mrad in the LPL pat- tern. Moreover, the peak flux of $\gamma$-ray reaches 1025 photons/s, which is considerably higher than existing $\gamma$-ray sources [53], for example, 106—9 photons/s in HI$\gamma$S and 105—10 photons/s in SLEGS, and the high $\gamma$-ray flux results not only from the ultra-short pulse duration, but also from the fact that the $\gamma$- ray flux of existing $\gamma$-ray sources is usually the average $\gamma$-ray flux.

In the CPL pattern, $\gamma$-rays are the most abundant in the beam region, followed by electrons, and positrons are the least numerous. The electron beam brilliance is 1.52 $×$1025 electrons/(s · mm2 · mrad2), and positron beam brilliance is 3.97 $×$1024 positrons/(s · mm2 · mrad2). Similarly, the $\gamma$-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 $\gamma$-rays and elec- trons have the highest energy in the beam region (up to 8 GeV), whereas the maximum particle energy of the positron beams is approximately 7 GeV. The average particle energy of the electron and positron beams, which is approximately

## 0.6 GeV, is higher than that of $\gamma$-ray beam ( 0.2 GeV).

In the LPL pattern, the beam brilliance, energy conver- sion efficiency, maximum particle energy, and average par- ticle energy of the particles have the same numerical or- der in terms of the three types of particles: $\gamma$-rays, electrons, and positrons. The $\gamma$-ray and electron beam brilliances are 8.89 \$×\$1026 photons/(s ·mm2 ·mrad2) and 1.05 \$×\$1025 electrons/(s ·mm2 ·mrad2), respectively. The energy conver- sion efficiency of $\gamma$-rays is 5.96%, which is marginally higher than the 2% given by the all-optical scheme for laser energy into $\gamma$-rays in 2012 [80]. The energy conversion efficien- cies of electrons and positrons are 0.19% and 0.09%, respec- tively. The maximum particle energies are similar to those in the CPL pattern. The average particle energy of the electron and positron beams is approximately 0.4 GeV, and the aver- age particle energy of the $\gamma$-ray beam is approximately 0.2 GeV. Although the maximum energy of $\gamma$-rays approaches the initial electron energy during the collision process, most of the $\gamma$-rays still have lower energy. Meanwhile, most of the positrons have higher energies.

In general, the energy conversion efficiency of particles in the CPL pattern is lower than that in the LPL pattern, and 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 attributed to the fact that more positrons are generated with lower energy and greater spatial emittance in the beam region in the LPL pattern. The CPL pattern demonstrate superior beam quality for generating $\gamma$- rays and electrons, whereas the LPL pattern may achieve higher beam quality for generating positrons in SHINE.

C. Facility layout and specific applications The simulations in this work provide an alternative way to produce high-quality $\gamma$-ray and positron beams, which is dis- tinct from the all-optical scheme[81-83], where the UIUSL first generates a high-energy electron beam and then collides with another UIUSL. The simulated results are aimed at as- sessing the feasibility and advantages of electron-laser col- liding $\gamma$-ray source and positron beam facility, which provide new opportunities for high-energy photonuclear reac- tions and positron-related physics within the aforementioned energy ranges. Examples of different ($\gamma$, \$ 0), ( , *abs*)*and*( \$, f) reactions within the high-energy scope are plotted in Fig. 6, which could enhance the comprehensive understand- ing of nuclear structures, such as form factors, polarization, and resonances [84], and the high brilliance and high flux of the particle beams may partly advance the nuclear reaction yield. Furthermore, as shown in Fig. 7 Figure 7: see original paper-(d), the maximum energies of $\gamma$-rays and positrons vary with momentum angle $\theta$y in the beam region at 700 fs, particularly when the energy exceeds 100 MeV. $\gamma$-rays near the 0 degree momentum angle with energies below 100 MeV have the highest proportion.

Positrons around the 0-degree momentum angle with energy above 100 MeV have the highest proportion.

A 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(e). First, the spatial distri- butions of the three types of particles overlaps, as demon- strated by the simulated results.

In addition, beam separa- tion can be achieved by placing deflecting magnets around the beam region [45, 85, 86]. Finally, neutral $\gamma$-rays propa- gate in the positive direction along the X axis, whereas elec- trons and positrons propagate in opposite directions along the Y axis [44, 82, 87]. Particle energies follow a continu- ous spectrum defined by the surrounding temperature in the high-temperature, high-density plasma of extreme astrophysi- cal environments, including $\gamma$-ray bursts in active galactic nu- clei, pulsars, stellar interiors, supernovae, neutron star merg- Fig. 7. (Color online) (a) and (b) are respectively the $\theta$y-Ek dia- grams of $\gamma$-rays and positrons in the beam region under the CPL pattern, and (c) and (d) are respectively the $\theta$y-Ek diagrams of $\gamma$- rays and positrons in the beam region under the LPL pattern, with the particle energy of 100 MeV marked by the dashed line. (e) is a sketch drawing of a colliding station and its high-energy $\gamma$-ray and positron beamlines based on the SEL 100 PW laser and SLA 8 GeV electron beam in SHINE [17], and its specific applications. ers, 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 $\gamma$-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 $\gamma$-ray beams in SHINE would significantly promote the nuclear reaction research and strange phenomena in nu- clear physics and nuclear astrophysics. Ultra-intense $\gamma$-rays are ideal for studying the photonuclear reactions of short- lived unstable nuclides with high cross-sections and minimal rare nuclide target material [88], and $\gamma$-ray-assisted multipho- ton fusion processes [89].

However, several questions remain regarding both the tech- nique and theory. One is how to achieve collisions by syn- chronizing the electron beam and laser within a few microns and femtoseconds [90–92], which requires extremely high initial beam quality and technical precision [51, 93, 94]. This might be solved by using a spherical mirror to control the col- lision angle and by triggering the SLA electron beam with a laser pulse that shares the seed of the SEL 100 PW laser for precise time control. Another question is whether the max- imum energy of the three types of particles may exceed the maximum energy of the initial electron beam, which requires increasing the electron beam energy of the accelerator to ob- tain higher $\gamma$-ray and positron beam energies. The third is that the aforementioned applications, such as those involving photonuclear reactions, necessitate the development of detec- tors with higher sensitivity and the exploration of theoretical models under extreme conditions.

V. CONCLUSION A comprehensive simulation was performed on particle productions in collisions between the SEL 100 PW laser and SLA 8 GeV electron beam based on SHINE using the PIC program SMILEI. Most of the $\gamma$-rays and electron-positron pairs generated by the NICS and MBWP were localized at the beam center, where the beam center size matched that of the initial electron pulse. The majority of $\gamma$-rays are distributed in the lower energy range (Ek $<$ 0.9 GeV), and the generated electrons and positrons are concentrated at Ek $=$ 0.2 GeV for CPL and Ek $=$ 0.1 GeV for LPL. Electrons and positrons moved forward in the beam center, whereas those in the "tail end" spread out in three-dimensional space for the CPL pat- tern and in the X and Y directions for the LPL pattern. Within the selected beam region, the angles of the particle momen- tum were clustered around 0 ◦ , and the beam brilliance in- creased with increasing laser intensity. The beam brilliance of the $\gamma$-rays, with a maximum energy of up to 8 GeV, reached 1027 photons/(s · mm2 · mrad2). The beam emittance was ap- proximately 0.1 mm · mrad in the CPL pattern, and its energy conversion efficiency was up to 5.96% in the LPL pattern.

The maximum energy of positrons reached 7 GeV, with a beam brilliance of up to 4 × 1024 positrons/(s · mm2 · mrad2), a beam emittance of approximately 0.1 mm · mrad in the CPL pattern, and an energy conversion efficiency of 0.09% in the LPL pattern. High brilliance, high energy, and low emittance are the advantages of the $\gamma$-ray, positron, and electron beams, which are generated in simulated collisions. The $\gamma$-ray beam brilliance was higher, and the beam emittance was lower in [1] H. Chen, L. M. Zheng, B. Gao et al., Beam dynamics opti- mization of very-high-frequency gun photoinjector. Nucl. Sci.

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In addition to quantitatively and comprehensively assess- ing top-quality $\gamma$-ray and positron beams with the most in- tense laser, this work explores the feasibility of the facility design scheme. Multiple frontier applications have been pre- sented with these $\gamma$—ray and positron beams, including $\gamma$-ray microscopy in material science and engineering, $\gamma$-ray spec- trum diagnostics of radionuclides, positron emission tomog- raphy (PET) for advanced nuclear analysis technology, and others. Moreover, if the particle beams, including the elec- trons of the SLA and the SEL 100 PW laser [95], can be po- larized [96–98] and vortexed [99], they will have significant potential to enhance the research in plasma physics and ad- vance studies in nuclear physics and astrophysics [100, 101].

DATA AVAILABILITY support the findings of The data that openly available https://cstr.cn/31253.11.sciencedb.j00186.00760 https://www.doi.org/10.57760/sciencedb.j00186.00760.

Science Data Bank study DECLARATIONS Conflict of interest Chun-Wang Ma and Xi-Guang Cao are the editorial board members for Nuclear Science and Tech- niques and were not involved in the editorial review or the deci- sion to publish this article. All authors declare that there is no conflict of interest. [5] V. G. Nedorezov, S. G. Rykovanov, A. B. Savel' ev, Nuclear photonics: results and prospects, Phys. Usp. 64, 1214-1237 (2021). doi: 10.3367/UFNe.2021.03.038960 [6] P. G. Thirolf, D. Habs, M. Gross et al., Laser ion acceleration: status and perspectives for fusion. EPJ Web Conferences 17, 11001 (2011). doi: 10.1051/epjconf/20111711001 [7] W. Su, X. Cao, C. Ma et al., Multi-layer phenomena in petawatt laser-driven acceleration of heavy ions. Plasma Sci.

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