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Quasi-monoenergetic positron beam generation from ultra-intense laser-matter interactions

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In ultra-intense laser-matter interactions in which the radiation reaction effect plays an important role, γ-rays are effectively generated that are intense, collimated, and of short duration. These γ-rays propagate through the target, which results in the electron-positron pair creation caused by the interaction of the γ-rays with the nuclear electric fields. The positron beam thus generated has several unique features; it is quasi-monoenergetic in nature with a peak energy of hundreds of MeV, well collimated, and of ultra-short duration. Based on the numerical simulations, the dependences of the number and monochromaticity of the positrons on the laser and target parameters are explored, which leads to the proposal of a new type of the laser-driven positron source. Published by AIP Publishing. [http://dx.doi.org/10.1063/1.4965914]

I. INTRODUCTION

Developments in laser technologies have resulted in continuous increases in the laser focus intensity, giving rise to new research fields such as high energy density physics. In laser-matter interactions in the relativistic regime, high-density electrons with relativistic energies are generated by laser-plasma interactions. The transport of these electrons induces various structures inside plasmas. These plasma structures are utilized to generate various types of quantum beams, such as beams of electrons, ions, and x-rays.

Quantum beams consisting of positrons are also attractive because of their wide range of applications, in fields such as medical diagnostics, materials science, and laboratory astrophysics. At present, positrons produced by conventional electron accelerators suffer from the disadvantage of a wide and continuous energy spread. By contrast, one of the advantageous features of laser-driven positron production is the quasi-monoenergetic nature of the resulting energy distribution. If such a quasi-monoenergetic positron beam could become available in the near future, it would enable a new frontier in science using positrons. The generation of positrons from the laser-plasma interactions has been investigated both theoretically and experimentally. In the previous laser-plasma experiments, positrons have been generated using high-energy electrons or the Bremsstrahlung γ-rays they produce, which interact with the nuclear electric fields. High-energy electrons are generated by the laser-plasma interactions, and these electrons propagate through the solid target and emit Bremsstrahlung γ-rays. These Bremsstrahlung γ-rays then interact with the nuclear electric fields, leading to electron-positron pair creation through the Bethe-Heitler (BH) process. In recent experiments, 1012 positrons per bunch were obtained using thick (millimeter-scale) high-Z solid targets. Positron generation from the high-energy electrons has also been observed in experiments using a two-target system, in which the first target (gas target) produced laser-accelerated electrons and the second target (solid target) acted as a converter for which the electrons generated electron-positron pairs via the trident process. In this scheme, 105 positrons with a peak energy of 100 MeV and an energy spread of δE/E ~ 1 were attained.

In the high-intensity regime of the laser-plasma interactions where the radiation reaction effect plays an important role; the motion of electrons under the intense laser field becomes dissipative. When such an intense laser beam irradiates a solid target, the laser energy is effectively converted into photon energies in the γ-ray regime. The generated γ-rays are intense, well collimated, and as short in duration as the incident laser pulse. These γ-rays are locally generated at the front of the target, i.e., in the laser-plasma interaction region, and then propagate through the target while interacting with the atoms and nuclei through the processes such as Compton scattering, electron-positron pair creation, and photonic reactions. This results in the generation of nucleons and electron-positron pairs that are expected to have unique features such as high density, good collimation, and short bunches. In our previous work, using a Particle-In-Cell code including the γ-ray transport processes discussed above, it was shown that positrons and neutrons are effectively generated by the transport of laser-driven γ-rays through a target via the BH process and photonuclear reactions. However, quantitative analyses of the monochromaticity of positron beams and the parameter dependence of this monochromaticity on the laser and target parameters have not been performed. It has also been shown that positrons can be generated from laser-plasmas via the nonlinear Breit-Wheeler process. This process becomes of interest in the high intensity regime of I ≥ 1025 W/cm2; however, this regime is outside the scope of this paper, and we instead focus our attention on the regime in which the quantum effect on the radiation reaction is negligible, i.e., for the Lorentz- and gauge-invariant parameter λ= eℏ\sqrt{(F_μνp_μp_ν)^2/m^2c^4} ≪ 1.

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Here, $e$, $m$, $c$, and $h$ are the charge of the electron, the electron rest mass, the electric charge, the speed of light, and Planck’s constant, respectively, and $F_{\mu\nu}$ and $p_{\mu}$ are the field tensor and four-momentum, respectively.

In this paper, we investigate in detail the characteristics of positrons generated by the transport of laser-driven $\gamma$-rays that are generated via the radiation reaction effect and explore their dependences on the laser and target parameters, particularly with respect to the monochromaticity of the positron beam, and use the results of this investigation as a basis for proposing a new type of laser-driven positron source with unique features. In Section II, we present the characteristics of positron beams emitted from solid targets irradiated with ultra-intense laser pulses. In Section III, the dependences of the number of positrons and their monochromaticity, i.e., their relative energy spread, on the laser and target parameters are explored. On the order of $10^7$ positrons with a quasi-monoenergetic distribution are generated by irradiating solid targets with the optimal target parameters with laser pulses with an intensity of $I \sim 5 \times 10^{22}$ W/cm$^2$. A summary is presented in Section IV.

II. QUASI-MONO-ENERGETIC POSITRON BEAM GENERATION

We first explain the characteristics of positrons that are emitted from a target that is irradiated with an ultra-intense laser pulse. A laser pulse with an intensity of $I = 5 \times 10^{22}$ W/cm$^2$, a duration of 30 fs, and a spot diameter of 4.2 $\mu$m (FWHM) irradiates a target consisting of fully ionized carbon with an electron density of $n_e = 345n_c$. Here, $n_c = \alpha^2m_0e^2$ is the critical density for a laser angular frequency of $\omega_0$ and $\epsilon_0$ is the permittivity of vacuum. The target thickness is 1 $\mu$m, and the target is located at $30 \leq x[\mu$m] $\leq 31$ in a simulation box with dimensions of 80 $\mu$m $\times$ 90 $\mu$m (Fig. 1(a)). A pre-plasma with a scale length of $L = 2.5\mu$m is located to the left side of the target. A laser pulse with a wavelength of 0.8 $\mu$m, which is polarized in the $y-$ direction, irradiates the target from the left-hand side. The interaction of the intense laser pulse with the target generates high-energy electrons and $\gamma$-rays in the interaction region. The generated $\gamma$-rays are collimated in two directions, at the deviations of $\pm 30^\circ$ from the laser axis, and are confined to the laser polarization plane. These $\gamma$-rays propagate through the target and interact with the nuclear electric fields, generating electron-positron pairs through the BH process. Figure 1 shows the temporal history of the positron number density distribution at $t = 150, 170$, and 220 fs. Here, the positron number density is normalized with respect to $n_c$, and the laser field with its peak intensity reaches the target at $t \approx 145$ fs. The dashed line indicates the position of the target’s rear surface. In Figs. 1(a) and 1(b), it is observed that there are two regions in which the generated positron beam intensities are relatively high (indicated by the arrows in the figures), where the $\gamma$-ray emission is also intense. A fraction of the generated positrons escape through the rear surface, and the others are reflected at the rear surface. The positrons emitted from the rear surface are collimated and form a short bunch, as shown in Fig. 1(c).

FIG. 1. Temporal history of the positron number density at (a) $t = 150$, (b) $t = 170$, and (c) $t = 220$ fs. The positron densities are normalized with respect to the critical density $n_c$. The dashed lines indicate the target’s rear surface, and the arrows in (a) and (b) indicate the two emission directions in which the positron beams are most intense.

The reflection of the positrons at the rear surface is caused by the strong magnetic field that is induced by the high-energy electrons flowing out through the rear surface. Figures 2(a) and 2(b) show the distributions of the magnetic and electric fields, which are normalized with respect to the
corresponding laser fields. The magnitude of the magnetic field is $1.43 \times 10^9 \text{ G}$, and its spatial extent in the $x$-direction is approximately $1.5 \ \mu \text{m}$. This surface magnetic field directs low-energy positrons back towards the inside of the target (see Figs. 1(b) and 1(c)), which results in the lateral transport of the low-energy positrons. High-energy positrons are only weakly reflected and are further accelerated by the sheath electric field. The maximum electric field intensity is $5.0 \times 10^{13} \text{ V/m}$, with a spatial extent of $1.7 \ \mu \text{m}$ in the $x$-direction. These two fields generate a quasi-monoenergetic positron beam emitted from the rear surface of the target.

As a result, the positrons generated via the BH process are composed of two groups. One consists of the high-energy positrons emitted from the rear surface, and the other consists of the low-energy positrons that propagate in the lateral direction inside the target. Figure 3(a) shows the energy and angular distributions of the positrons. The high-energy component is emitted at the angles of $\pm 30^\circ$ from the laser axis, whereas the low energy component is collimated in the lateral direction. Figure 3(b) shows the energy spectra of the positrons, where the spectrum for the positrons emitted from the rear surface is plotted in black and that for the positrons propagating in the lateral direction is shown in red. The spectrum of the high-energy positrons has a spectral peak at $220 \text{ MeV}$, and the energy spread is $38 \text{ MeV}$ (half-width at half-maximum), yielding an evaluation of the relative energy spread as $\delta E/E \sim 0.17$. The number of positrons in the high-energy component is $9.1 \times 10^4$, and that in the low-energy component is $1.9 \times 10^5$, indicating that roughly one-third of the total positrons are emitted from the rear surface. In terms of the energy ratio, however, 90% of the total positron energy is carried by the high-energy component.

III. LASER-DRIVEN POSITRON SOURCE

The high-energy positrons emitted from the target’s rear surface exhibit several attractive features, such as monochromaticity with a peak energy of hundreds of MeV, a duration as short as the incident laser pulse, and good collimation comparable to that of the laser-driven $\gamma$-rays. To serve as a basis for the proposal of a laser-driven positron source with these unique features, we performed a series of simulations to clarify the dependence on the laser and target parameters of the number and monochromaticity of the high-energy positrons.

Figure 4(a) shows the dependence of the number of high-energy positrons on the target thickness. Here, the target is a fully ionized carbon target attached to a pre-plasma with a scale length of $\ell = 2.5 \ \mu \text{m}$. The laser intensity is

FIG. 2. The field distributions at $t = 160 \text{ fs}$. (a) The electric field normalized with respect to the laser electric field, which is $4.6 \times 10^{14} \text{ V/m}$. (b) The magnetic field normalized with respect to the laser magnetic field, which is $1.6 \times 10^{10} \text{ G}$.

FIG. 3. (a) Energy and angle distributions of the positrons. The high-energy positrons are emitted at the angle of $\pm 30^\circ$, where the laser axis corresponds to $0^\circ$. (b) Energy spectra of the positrons that are emitted from the rear surface (black) and the positrons that are propagating in the lateral direction (red).
$I = 5 \times 10^{22} \text{ W/cm}^2$, and the pulse duration is 30 fs. The γ-ray characteristics depend on the conditions of the laser-plasma interaction but not on the target thickness $L$. The reaction cross section of the BH process also does not depend on $L$. Therefore, the number of positrons increases linearly with $L$ because the interaction conditions are identical. This linear dependence saturates for targets thicker than the millimeter-scale because of photon absorption and relaxation processes.\textsuperscript{29} However, for quasi-monoenergetic positron beam generation, a relatively thin target is preferred because of the localization and simultaneity of the positron acceleration, as shown in Fig. 4(b). Figure 4(b) shows the relative energy spread, $\delta E/E$, as a function of the target thickness. The relative energy spread decreases with decreasing target thickness because the energy spread $\delta E$ decreases with decreasing target thickness, whereas the spectral peak energy $E$ does not depend on $L$ in this parameter regime. The dependence of $\delta E$ on the target thickness can be explained as follows. As the positron beam propagates, the area of the positron beam in the plane that is perpendicular to the propagation direction increases because of the divergence of the beam. For a thin target, the increase in the beam area is small or comparable to the initial beam area, and the acceleration on the rear surface is spatially and temporally localized, leading to a narrow energy spread. As the target thickness increases, the area of the positron beam increases and the acceleration on the rear surface begins to occur at different times and different positions, and consequently at the different sheath intensities, leading to a larger energy spread. The peak energy of the spectrum does not strongly depend on $L$ for the considered target thicknesses, since the γ-ray and electron energy spectra do not depend on $L$. A large angular spread and a large number of high-energy electrons lead to a relatively small difference in the sheath intensity over the short period of positron acceleration. As a result, the relative energy spread increases, i.e., the monochromaticity decreases, with increasing target thickness, and it can therefore be concluded that a thin target is needed for quasi-monoenergetic positron beam generation.

Figure 5(a) shows the dependence of the number of positrons on the laser intensity, $I$, where the target is a carbon target of 1 µm in thickness with a scale length of $\ell = 2.5 \mu m$. The number of high-energy positrons increases non-linearly with increasing laser intensity, and the relation is fitted to a function of the form $N_p \propto I^{2.5}$. Here, the number of photons scales as $N_\gamma \propto I^{1.5}$ because the energy conversion scales with $n_{\text{laser}} \propto I$, while the characteristic photon energy scales as $\omega_c \propto I^{0.5}$, as observed in the range of $1 \times 10^{22} < I \text{ [W/cm}^2]\text{] < } 1 \times 10^{23}$. The cross section of the BH process increases with increasing photon energy. Overall, all contributing processes give rise to the scaling of $N_p \propto I^{2.5}$ observed in the simulation. A similar dependence has also been observed in
The dependence of the number of positrons on the atomic number of the target material is plotted in Fig. 6(a). Because neither the number nor the energy spectrum of laser-driven $\gamma$-rays depends on the target material as long as the target electrons are sufficiently dense, the number of positrons is simply proportional to $Z^2$, as the dependence of the cross section of the BH process, i.e., $\sigma \sim (\alpha Z^2)$, where $\alpha$ and $n_e$ are the fine structure constant and the classical electron radius, respectively. The energy spread of the positrons does not depend on the target material because the laser-plasma interactions were the same regardless, as shown in Fig. 6(b). In these calculations, the interaction conditions were set to be nearly identical, i.e., the density gradient and the maximum electron density where the laser field interacts with the target are the same.

This means that the initial electron density was set sufficiently high for the laser pulse not to penetrate through the target. In the simulations, the initial degrees of ionization of the target materials (and the resultant initial electron density) were assumed to be $\text{Be}^{1+}$ $(284 n_e)$, $\text{C}^{6+}$ $(345 n_e)$, $\text{Al}^{11+}$ $(383 n_e)$, $\text{Cu}^{19+}$ $(919 n_e)$, $\text{Au}^{21+}$ $(703 n_e)$, and $\text{Au}^{28+}$ $(943 n_e)$. Here, we simply assumed that the ionization induced by irradiation with the pre-pulse and/or the foot of the main-pulse proceeded up to the electronic state with an ionization potential of 1000 eV. The assumption of this highly ionized state is based on a crude estimate using the ionization rate model

$$\nu(E) = 4 \omega_a \left( \frac{I_a}{I_h} \right)^{5/2} \frac{E_a}{E} \exp \left[ -\frac{2}{3} \left( \frac{I_a}{I_h} \right)^{3/2} \frac{E_a}{E} \right].$$  

(1)

Here, $\omega_a = me^4/(4\pi\epsilon_0)^2\hbar^3$, $E_a = m^2e^5/(4\pi\epsilon_0)^3\hbar^4$, and $E$ is the laser electric field. $I_a$ and $I_h$ are the ionization potentials of the atom under consideration and hydrogen, respectively. The condition for an atom with an ionization potential of 1000 eV to be ionized within half of the laser period is evaluated to be $\nu \pi/\omega_0 \sim 1$, which yields a quantitative condition for the laser intensity of $I \geq 6.8 \times 10^{20}$ W/cm$^2$. This intensity is realized at the foot of the main pulse in the regime in which the radiation reaction effect plays an important role.

Therefore, in our calculations, we simply assumed that the initial ionization degree corresponded to the state for which $I_a \leq 1000$ eV. Then, to see the how the modeling of the initial electron density affects the results presented in Figs. 6(a) and 6(b), we performed simulations in which the initial ionization degree of a carbon target was varied, considering states of $\text{C}^{1+}, \text{C}^{2+}, \ldots$, and $\text{C}^{6+}$. Figure 6(c) shows the dependence of the number of positrons on the initial electron density, where the atomic density is $57.5 n_e$ for all cases, which corresponds to a mass density of 2.0 g/cm$^3$. The number of the positrons does not depend on the initial electron density for $\text{C}^{1+} \sim \text{C}^{6+}$, and it is decreased for $\text{C}^{1+}$ and $\text{C}^{2+}$. This tendency seems to change at $n_e \sim 160 n_e$. The density of $n_e = 160 n_e$ corresponds to the relativistic critical density $n_{\text{cr}} = n_e \sqrt{1 + a_l^2/2} \sim 160 n_e$, where $a_l$ is the normalized laser intensity of the self-focused laser pulse. As long as the electron density is higher than the relativistic critical density and the interaction conditions are comparable, the numbers of $\gamma$-rays and positrons do not change since the cross section of the BH process depends on the atomic density but not the electron density. Therefore, the number of the positrons does not depend on the assumption of the initial ionization degree.
when the laser field is sufficiently intense to highly preionize the target, i.e., \( n_e \geq n_{\text{rel}} \). For the case of intense laser pulse irradiation in which the radiation reaction occurs, the initial electron density is expected to be higher than \( n_{\text{rel}} \) for a variety of solid targets. Notably, a gas density target is less effective for quasi-monoenergetic positron beam generation. By properly choosing the target material, the optimal value of the scale length for the number of positrons produced can be enhanced by using a high-Z material. The optimal value of the scale length for the number of positrons coincides with that for the monochromaticity of the positrons. As an example, the irradiation of a thin gold target with a pre-plasma scale length of \( \ell = 2.5 \mu m \) with a laser pulse of \( I = 5 \times 10^{22} \text{ W/cm}^2 \) and a duration of 30 fs will generate \( 10^7 \) positrons with quasi-monoenergetic distribution with \( \delta E / E = 0.17 \), a peak energy of 216 MeV, and a duration of 30 fs. The positron beams generated by laser-driven \( \gamma \)-rays exhibit unique features of high energy, quasi-monochromaticity, good collimation, and ultra-short duration. Further investigations of the proposed positron beam source will enable applications such as source beams for electron-positron beam colliders.

**IV. SUMMARY**

We performed numerical analyses to explore the generation of positron beams using laser-driven \( \gamma \)-rays, which is a new approach for the design of laser-driven positron sources. The positrons generated from laser-driven \( \gamma \)-rays exhibit advantageous features of high energy, quasi-monochromaticity, and good collimation with a reasonable abundance. This scheme...
uses a simple geometry consisting of a single solid target irradiated with a laser pulse. It has been shown that the irradiation of a high-Z thin target with an optimal pre-plasma scale length with a laser pulse with an intensity of $5 \times 10^{22}$ W/cm$^2$ and a duration of 30 fs will produce $10^{13}$–$10^{16}$ positrons with an energy of $E \sim 220$ MeV and a relative energy spread of $\delta E/E = 0.17 – 0.3$. These laser parameters will be realized at high-power laser facilities in the near future.$^{14}$

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