Dense electron-positron plasmas and gamma-ray bursts generation by counter-propagating quantum electrodynamics-strong laser interaction with solid targets

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I. INTRODUCTION

The focused laser intensity has been increased dramatically in the last decade. At present, maximum intensities in excess of $10^{22}$ W/cm$^2$ are available in laboratories.\textsuperscript{1,2} When such intense laser pulses interact with matter, relativistic plasmas are produced. In addition to being of fundamental interest, such plasmas are also sources for many applications such as advanced particle accelerators,\textsuperscript{3–5} next generation of radiation sources,\textsuperscript{6,7} and laboratory environment for modeling of astrophysical phenomena.\textsuperscript{8,9}

Within the next few years, powerful lasers may be able to realize intensities of $10^{23}$–$10^{24}$ W/cm$^2$, enabling even more novel physical processes in the ultra relativistic plasma regime.\textsuperscript{10,11} At this intensity level, the radiation reaction and quantum electrodynamics (QED) effects will become important.\textsuperscript{11–15} As one of the QED effects, electron-positron pair plasma (EPPP) creation in strong laser fields has recently attracted a lot of attention.\textsuperscript{15} The EPPP can be produced via avalanche like electromagnetic cascades: the seed charged particles are first accelerated in the laser field, and then they emit energetic photons. The photons in turn decay in the laser fields and create electron-positron pairs. These electrons and positrons are accelerated in the laser fields and generate more photons and electron-positron pairs. In this case, the QED effects strongly modify the plasma dynamics by generating more charged particles and currents into the plasmas. Conversely, the rates of the QED processes also depend on the electromagnetic fields which are determined by the plasma dynamics. As a result, the QED processes and the plasma dynamics must be treated simultaneously and self-consistently in the so-called “QED-plasma” regime.\textsuperscript{16}

Since the coupling between the QED processes and plasma dynamics in realistic laser-produced QED-plasma is very complicated, numerical modeling seems to be the only way to clearly explore such interaction in recent years. In this paper, we use the simulation tool, QED effects included in the code. Such QED-PIC code has already been used to demonstrate the prolific generation of $\gamma$-rays and
electron-positron pairs, and the interplay between QED effects and collective processes in plasmas generated by next-generation 10 PW lasers. Note that recently several other PIC codes, coupling a quantum treatment of γ-ray photon and pair creation, have also been used to self-consistently simulate cascades of electron-positron pair production in pulsar atmospheres and in the interaction of two counter-propagating 100 PW (I = 3 × 10^{24} W/cm²) laser pulses.

In our studies, two-dimensional simulations are performed to investigate and compare the generation of dense EPPPs and γ-ray bursts from thin foil targets irradiated either on two-sides by two counter-propagating laser pulses or on one-side by a single laser pulse. Details of the γ-ray photons and electron-positron pairs generation process, the dynamical behaviors of the QED-plasma, and the resulting energy conversion efficiencies from laser to γ-ray photons and positrons are studied. We found that the two-side irradiation configuration has more advantages in obtaining higher conversion efficiency from laser to γ-ray photons and positrons and producing denser plasmas of electron-positron pairs. The reason for the prolific pair and photon production is mainly because that two counter-propagating laser pulses irradiate and compress the solid foil symmetrically and then it results in an electric potential well and a standing wave formed by the overlap of the incident and reflected laser pulses.

II. STRONG-FIELD QED PROCESSES

In QED dominated regime an electric field (E) should be treated as strong field if it exceeds the Schwinger limit: \(E \geq E_{\text{crit}} = me^2/|\langle e| \lambda_C|\rangle = 1.3 \times 10^{18} \text{ V/m}^{2}\). Such strong field is potentially capable of providing over an acceleration length of the Compton wavelength (\(\lambda_C = \hbar/(mc) \approx 3.9 \times 10^{-11} \text{ cm}\)) an energy \(E \) to a charge (\(e = -|e|\)) which exceeds the electron rest mass energy \(E > mc^2\) and thus separates virtual electron-positron pair. The Schwinger field required for such spontaneous electron-positron pair creation out of the vacuum would be attained at a laser intensity of roughly \(10^{20} \text{ W/cm}^2\). These have been intensively studied in theory but not yet been observed in experiments. Detailed calculations predict that observable consequences of this phenomenon might be obtained at intensities as low as \(10^{16} \text{ W/cm}^2\) using special interaction geometries; however, these are still unlikely to be achieved within the next few years.

Although the vacuum breakdown is far beyond of current laser intensities, several other strong-field QED effects will soon be experimentally accessible with the 10–100 PW lasers under construction. In O(10 PW) laser-plasma interactions, the dominant nonlinear QED effects are pair creation from high-energy photon (\(\gamma_b\)) through multi-photon Breit-Wheeler (BW) process, \(\gamma_b + n\gamma_1 \rightarrow e^+ + e^- \), and high-energy photon emission from electrons in the electromagnetic fields of the laser by nonlinear Compton scattering (CS) process, \(e^- + n\gamma_1 \rightarrow e^- + \gamma_b\), where \(\gamma_1\) represents a laser photon. These effects only become important at ultra-high laser intensities reached in 10 PW laser-plasma interactions and are typically characterized by the dimensionless invariants \(\eta = e\hbar/|\langle e| \lambda_C|\rangle|\) and \(\gamma = e\hbar^2 me^2/|\langle e| \lambda_C|\rangle| = \hbar \omega E_{\text{crit}} + (ck/k) \times B/2me^2 E_{\text{crit}}\), where \(\hbar\) is the Planck constant, \(\hbar \omega (\hbar k)\) is the γ-ray photon energy (momentum), \(F_{\mu\nu}\) is the field-strength tensor, \(p^\mu (k^\nu)\) is the electron’s (photon’s) four-momentum, \(\beta\) is the electron velocity normalized by the speed of light in vacuum \(c\), \(\gamma\) is the corresponding Lorentz factor, and \(E_{\text{crit}}\) is the component of the electric field perpendicular to the direction of particle motion.

The parameter \(\eta\) determines the γ-ray photon emission by electrons with relativistic energies, while \(\gamma\) determines the interaction between high-energy photons and the field. Strong-field QED effects become important when these parameters reach unity. For a 10 PW laser operating at an intensity of \(10^{23} \text{ W/cm}^2\), the laser electric field is \(|E| \approx 10^{15} \text{ V/m}\). When such a laser interacts with a solid target electrons can be directly accelerated to a \(\gamma\) of the order of several hundreds, and so the parameter \(\eta\) can approach unit. As a result, the γ-ray photons (\(\hbar \omega = 2\gamma mc^2\gamma/\eta\)) will take a large fraction of the accelerated electron’s energy \(\hbar \omega = 0.44\eta \gamma mc^2\), implying \(\gamma = 0.22\eta^2\) and since the mean free path of these γ-rays to pair creation is on the order of microns, this will result in the production of many electron-positron pairs. Previous studies show that a single 10–100 PW laser beam striking an overdense solid target may offer an attractive route to generate EPPPs. In addition, two counter-propagating beam configuration at similar laser intensities will create more appropriate conditions for pair production than a single laser beam. In the following, we study these processes by use of computer simulations. We extend the research of Ridgers et al. to the counter-propagating laser solid interaction.

III. 12.5 PW LASER-SOLID INTERACTIONS

Two laser-solid interaction cases are studied: (i) a single laser pulse with intensity of \(4 \times 10^{23} \text{ W/cm}^2\) incident on a thin solid foil, i.e., one-side irradiation case and (ii) two counter-propagating laser beams with identical intensities incident on the same solid foil, i.e., two-side irradiation case, as shown in Fig. 1. The simulation box sizes are \(8\lambda_L \times 8\lambda_L\) for single-side interaction case and \(9\lambda_L \times 8\lambda_L\) for two-side interaction case. The wavelength of the incident laser pulses is \(\lambda_L = 1 \mu \text{m}\). In both cases, the lasers are linearly p-polarized beams.
and focused to a spot with radius \( r = 1 \mu m \). The normalized vector potential is \( a_0 = eE/m_e c \omega_0 = 540 \), where \( \omega_0 = 2 \pi c / \lambda_i \) is the angular frequency of the laser. The laser pulses have transversely super-Gaussian spatial profile with electric field as \( \propto \exp(-y^2/1 \mu m^2) \) and temporally profile of \( P = P_0 = 12.5 \) PW for \( 0 < t < 30 \) fs and \( P = 0 \) elsewhere. They propagate from the boundaries of the simulation box at the time \( t = 0 \). The foil is a fully ionized aluminum with thickness of \( L = 1 \mu m \) and initial density profile of \( \rho(x, y) = 2.7 \text{ g/cm}^3 \) for \( 0 < x < L \) (single-side interaction) and \( 2 < x < L + 2 \) (two-side interaction) and \( \rho(x, y) = 0 \) elsewhere. Accordingly, the electron density of the fully ionized aluminum foil target \( n_e \) is \( 711n_c \), where \( n_c = m_e e^2 / e^2 \) is the critical plasma density for the incident laser pulse. The foil is discretized on a spatial grid with cell size of 10 nm and is represented by 1000 macroelectrons and 32 macroions per cell for both interaction cases.

### A. Single laser pulse incident on a thin solid target

Figures 2(a)–2(c) show the spatial density distributions of electrons, emitted \( \gamma \)-ray photons, and positrons for the one-side irradiation at \( t = 30 \) fs. At this moment, the electron density \( n_e \) is higher than the relativistic critical density \( n_c \) and the plasma is overdense to the incident laser pulse. Some of the incident pulse has been reflected from the solid surface. The light pressure compresses and deforms the thin foil target, and finally bores a hole into the solid foil, as shown in Fig. 2(a). The hole boring velocity is about \( 0.2 \times c \).\(^5\) The deformed (hole) area in the incident plane is approximately \( 2\lambda_0 \times 2\lambda_0 \). From Fig. 2(b), one can see that the spatial pattern of emitted \( \gamma \)-rays coincides well with the target deformation region, where most electrons are accelerated by the electric field.

Both the incident and reflected laser pulses make prolific positron production in the hole-boring area, as shown in Fig. 2(c). In our case, more than \( 10^9 \) positrons are produced and the positrons produced in the hole-boring front area have a maximum density of \( 8 \times 10^{26} \text{ m}^{-3} \), approaching the non-relativistic critical density for the incoming laser. The green dots in Fig. 2(d) show that the average energy of positrons distributed in the hole-boring front area (approximately 160 MeV) is much higher than the energy of photons in the same area. This indicates that the positrons are rapidly accelerated to high energy by the laser pulse after generation. The expected average energy of the positrons is \( \langle \gamma \rangle m_e c^2 \approx a_{sol} m_e c^2 \approx eE_{sol}^2/\omega_0 \approx 150 \) MeV, which is consistent with the simulation result. Here, \( E_{sol}^2 \) is the intensity of the laser electric field inside the solid (and the index HB denotes hole-boring).\(^6\) However, due to the presence of the sheath field generated by the fast electrons launched from the deformed foil,\(^9\) most positrons are further accelerated in the sheath field after direct laser electric field acceleration when they leave the target. This can be seen from the curved stripes with yellow color in Fig. 2(d). The sheath field confines the fast electrons (the majority species compared with positrons) inside the target and accelerates positrons,\(^30\) doing work \( \Phi_{m_e} c^2 \) which approximately equals to the fast electron energy. Here, \( \Phi \) is the sheath potential generated by fast electrons as they leave the target. From the simulation, the average positron energy is 321 MeV, approximately twice that of the positrons in the hole-boring front area.

### B. Two laser pulses counter-incident on a thin solid target

The studies above are basically similar as those found by Ridgers et al.\(^16\) however, situations are quite different when two-side irradiation geometry is used. Figures 3(a)–3(c) show the spatial density distributions of electrons, emitted \( \gamma \)-ray photons, and positrons from two 12.5 PW laser pulses counter-incident on the solid target at \( t = 36 \) fs. Compared with the one-side irradiation case, two-side irradiation enables irradiating and compressing the thin foil more symmetrically,\(^31\) forming a more stable structure with higher electron density at the irradiation region. During the compressing process, electrons inside the target are pushed forward by the ponderomotive force of the two incident lasers, resulting in a dumbbell-like structure as shown in Fig. 3(a). In this case, the formation of the sheath potential produced by fast electrons leaving the target is suppressed. Figs. 3(a)–3(c) also show that all the spatial density distributions of accelerated electrons, \( \gamma \)-ray photons and pairs manifest symmetrical patterns. Different patterns are seen in the case of one-side illumination with spatial non-symmetrical structures due to the asymmetrical irradiation of laser pulse on the thin foil.

![FIG. 2. The spatial density distribution of electrons (a), \( \gamma \)-ray photons (b), and positrons (c) for one-side irradiation at the moment of \( t = 30 \) fs. (d) The spatial energy distribution of positrons. The units of density and energy are \( \text{m}^{-3} \) and joule, respectively.](image-url)
Figures 3(b) and 3(c) show that both the $\gamma$-ray photons and pairs are generated with a higher number density and over a larger production area than that in the one-side irradiation case. The simulations show that MeV-level $\gamma$-ray source with an intensity of $1.6 \times 10^{14}$ s$^{-1}$ is produced, which is potentially the most intense $\gamma$-ray source available in the laboratory. It suggests that about 20% of the total laser energy is converted into $\gamma$-ray photons. The interaction is in the radiation dominated regime. In the two-side irradiation case, the $\gamma$-ray photon number density increases three times compared to that in the one-side case, and the production area doubles. It is of great interest that using two-side irradiation configuration can produce higher density EPPPs with a maximum number density above $6 \times 10^{27}$ m$^{-3}$, an increase of sevenfold compared to that in one-side irradiation scheme. This is mainly due to the accelerated electrons by laser electric field interacting sufficiently strongly with the incident and reflected wave from the counter-propagating laser pulses. One the one hand, similar as the one-side irradiation case, the electrons reach relativistic energies and emit high-energy photons, followed by generation of electron-positron pairs in the presence of the strong field that accelerates them. On the other hand, a considerable part of electrons on one side of the target foil penetrate into and even cross the overdense plasma and then interact successfully with the counter-incident laser pulse on the other side, contributing additional high-energy photons and pairs. However, such phenomenon is absent in the one-side irradiation case.

Another possible reason for the observed enhancement in the two-side irradiation case is that the solid target maintains a planar structure parallel to y-z plane (see Fig. 3(a)). Such a planar structure reflects the incident laser pulses and so doubles the electric field. The overlap of the incident and reflected laser pulses forms standing wave on both sides of the foil (see Figs. 4(a) and 4(b)). The resulting standing wave near the thin foil can further lead to an electric potential well around the focused target area (see Fig. 4(b)). Although the potential fields on both sides are not quasi-static, the electric potential well resulting from the laser fields always exists since the intensities of the electric fields vary simultaneously. Hence, the formation of the electric potential and standing wave around the target enhances the rates of the QED reactions. Comparatively, in the one-side irradiation case (seen in Figs. 4(c) and 4(d)) although the incident laser pulse also has a reflection from the solid surface and gives rise to an enhanced laser electric field, due to the stronger target deformation, the reflected wave shows focusing character and the transmitted wave shows defocusing character. And the positions of the strongest laser field and plasma density deviate from each other. The enhancement of $\gamma$-ray photons and pairs generation is largely reduced. The transmitted positrons and $\gamma$-ray photons are also dispersed quickly.

IV. COMPARISON AND DISCUSSION

As shown in Fig. 4(b), the electric potential well around the focused target area is formed by the standing waves for the two-side irradiation, which is different from the sheath
potential that can post-accelerate the positrons for the one-side irradiation. Such field structure can confine and bunch positrons and electrons. The positrons produced at the foil front are accelerated (or electrons decelerated) by the transverse electric field. But once the positrons cross the overdense plasma and arrive at the rear side of the foil, they can be decelerated (or electrons accelerated) by the similar electric field structure with opposite polarity. Same happens to the pairs produced originally at the rear side of the foil. This suggests that the majority of pairs will be gathered together and form a high-density EPPP with energy distribution with stripe like structures as shown in Fig. 3(d). On the contrary, in the one-side irradiation case, due to the absence of the electric potential around the target the positrons accelerated by the sheath field escape rapidly from the target deformation region and then spread out along with the transmitted laser in all directions (see Fig. 2(d)). We also should note that as the laser electric field and the resulting electric potential well disappear, the convection of the confined pairs takes place, which may be useful for observing the dynamics of the high energy density EPPPs experimentally.

Simulation results show in the case of two-side illumination, $1.6 \times 10^{14}$ $\gamma$-ray photons are produced with an average energy of 5.8 MeV and therein $6.7 \times 10^{13}$ $\gamma$-ray photons have energies greater than 1 MeV. This corresponds to 20.2% conversion of the laser energy (754 J. in total) to the energy of the $\gamma$-ray burst. As a comparison in the one-side illumination case, $4.7 \times 10^{13}$ $\gamma$-ray photons are produced with an average energy of 3.6 MeV and therein $1.0 \times 10^{13}$ $\gamma$-ray photons have energies greater than 1 MeV. Hence, the conversion efficiency from the laser energy (377 J. in the one-side case) to $\gamma$-ray energy is approximately ~7%, just one third of that in the two-side incidence case. The energy conversion efficiency from the laser to positrons $\eta_{pe}$ is also increased in the two-side irradiation case. It is 0.02% for the one-side incidence and 0.06% for the two-side incidence. Accordingly, the density of the EPPP increases from nearly $8 \times 10^{26} \text{m}^{-3}$ to $6 \times 10^{27} \text{m}^{-3}$, approximately 8 orders of magnitude larger than that generated by the one-side irradiation gold-target scheme.

Average positron energies are 321 MeV and 258 MeV for the one-side and two-side irradiations, respectively. These values are much higher than the average photon energy (a few MeV) and approximately twice that of the fast electrons (~140 MeV). This suggests that the positrons are born with relatively low energy and are then rapidly accelerated by the laser field to energies equal to that of the fast electrons and further accelerated by the sheath field when they leave the target as discussed above. Note that the average and the cut-off positron energies in the two-side incidence case are slightly smaller than those in the one-side interaction case due to a weaker sheath field compared with the one-side interaction condition. We summarized our results in Table I by showing the comparisons between the one-side and two-side incidence cases, in which the total absorption of the laser energy is approximately 20% and 35%, respectively.

We also compared the spectral distributions of electron and positron beams for the one-side and two-side incidences. Fig. 5 shows that both the electron and positron spectra in the two cases have similar distributions. However, the fast electron spectrum in the two-side incidence case has a lower cut-off energy (~750 MeV), compared with that in the one-side case. The reason is that the initially accelerated electrons are confined by the potential well of the transverse electric field (see Fig. 4(b)) and the electron’s synchrotron emission via nonlinear CS process are therefore enhanced, which then produce more $\gamma$-ray photons with higher energies as shown in Table I. As a result, the emitted electrons lose more energy in the two-side incidence case, resulting in an average kinetic energy of 124 MeV compared with 134 MeV in the one-side incidence case. Further, due to the presence of the electric potential around the target, positrons generated from the two-side illumination cannot escape from where they originate and therefore are not accelerated further by the sheath potential. As a result, the positron energy is lower than that from the one-side irradiation and therein a larger number of positrons experience post-acceleration, despite the fact that a maximum positron energy of 800 MeV could be achieved through direct laser electric field acceleration.

![Figure 5. The electron and positron spectral distributions in the one-side (solid line) and two-side (dotted line) irradiation case. The inset shows the corresponding $\gamma$-ray spectra.](image-url)
V. EXPERIMENTAL FEASIBILITY WITH COUNTER-PROPAGATING 10 PW LASER BEAMS

Currently, the Extreme Light Infrastructure-Nuclear Physics (ELI-NP) facility is planning to focus for the first time two counter-propagating 10 PW pulsed laser beams at intensities of $\sim10^{22}$ W/cm$^2$ and above, enabling experimental investigation of dense electron-positron plasmas and $\gamma$-ray bursts generation by counter-propagating QED-strong laser interaction with solid targets proposed here. Fig. 6 shows the counter-propagating focusing geometry for solid foil targets at the ELI-NP E6 interaction area, which will start operation in 2018. The 10 PW West-Laser-Beam (the Pump-beam) and the 10 PW East-Laser-Beam (the Probe-beam) are tightly focused in the E6 station with short focal length F:3 parabolic mirrors on the solid target at the interaction point. The Probe-Beam provides the strong EM field to generate the strong-field QED effects we want to study. A number of diagnostics will also be available for measuring: $\gamma$-rays, electrons, positrons, ions, scattered laser light, etc.

VI. SUMMARY AND CONCLUSION

In conclusion, we have shown that $O$(10 PW) laser-solid interactions will generate dense electron-positron plasmas and ultra-intense bursts of $\gamma$-rays. In these interactions, the dominant route to pair production involves the emission of $\gamma$-ray photons via nonlinear CS process, and their further conversion into electron-positron pairs via multi-photon BW process. We compared the effectiveness of the counter-propagating laser- and single laser-solid interaction configurations in producing a larger number of $\gamma$-rays and electron-positron pairs. In contrast to single laser-solid configuration, strong absorption of the laser energy occurs in counter-propagating laser-solid interaction, resulting in three times higher energy conversion efficiencies from laser to $\gamma$-ray photons and electron-positron pairs. A maximal positron density of $6 \times 10^{27}$ m$^{-3}$ can be achieved, which is 8 times denser than in single-side laser-solid irradiation case. Additionally, 20% of the laser energy is converted to a burst of $\gamma$-rays with a flux exceeding $10^{14}$ photons/s, which could be potentially the most intense high-energy $\gamma$-ray source available in the laboratory. Experiments using counter-propagating laser-solid interactions to investigate the QED effects in plasmas and produce prolific $\gamma$-rays and dense electron-positron pairs by the future extreme ELI-NP facility are in plan.

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