Ultraintense Laser-Driven Nonthermal Acceleration of Charged Particles in the Near-QED Regime

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Abstract

Here, we have studied the nonthermal acceleration of energetic electrons/protons under the near-QED regime by extending the laser intensity beyond 10^{23} W/cm² based on a two-dimensional particle-in-cell simulation. The radiation-reaction (RR) effect plays a critical role and brings a quantum stochastic effect to the charged-particle acceleration process. Background electrons in plasma are accelerated in an intense laser field to several GeVs with strong oscillations and thus radiate γ -ray photons. The emitting γ -photons have a broad energy spectrum with maximal energy up to 3 GeV and result in radiation-reaction trapping of the electrons, forming a relativistic plasma bunch in the plasma channel. The accumulation of electrons and protons produces a charge-separation field for the acceleration/deceleration of charged particles. The accelerated electrons have a nonthermal spectrum with a power-law index of 1.5 with a laser intensity 10^{23} W/cm² lower than that in the non-QED regime. As the laser intensity further increases over 10^{24} W/cm², the power-law index further drops to 1.2. Moreover, the energy spectrum of accelerated protons has a nonthermal distribution with a power-law index of 0.7, which is much lower than that of electrons in the near-QED regime.

Introduction

The origin and acceleration of cosmics are always unresolved issues¹. Plasma wakefield collective accelerators, which can provide extremely high acceleration over a short space distance, have been proposed as a potential cosmic-ray acceleration mechanism^{2,3}. In astrophysical environments, wakefields can be excited by magnetowaves in relativistic astrophysical outflows⁴ or by large amplitude precursor waves upstream of shockwaves⁵. The latter involves a series of processes from shockwave formation to particle acceleration in the wakefield⁶. It is difficult to take a direct observation of astrophysical parameters in extreme celestial events limited by the current technology. The acceleration process of high-energy charged particles based on relativistic laser plasma interactions has been studied, which provides a superhigh acceleration gradient⁷. Kuramitsu et al. reported the simulation of a large-size relativistic laser-induced incoherent wakefield in low-density plasma. The result shows that the nonthermal spectrum of accelerated energetic electrons has a universal power-law index of ~ 2 , which is reproduced by subsequent model experiments^{8,9}. The relativistic laser used in these works is less than 10^{22} W/cm², and the influence of the radiation process on electron motion is not considered.

The current 10 PW and even future 100 PW laser facilities will provide an intense femtosecond laser pulse with a power density of 10^{22-24} W/cm² and a focal spot size of a few micrometers¹⁰⁻¹³. Laser-plasma interaction employing such an intense laser pulse enters the so-called moderate quantum electrodynamic (or near-QED) regime¹⁴⁻¹⁸. Electrons in the laser field are accelerated to GeV in a short time. At the same time, these high-energy electrons oscillating in the laser field discretely radiate high-energy γ -photons and suffer RR recoil forces¹⁹⁻²¹. Radiation events occur randomly or probabilistically, and the energy of a single emitted photon is equivalent to that of an electron, which seriously affects the electron dynamics. Under the influence of the RR trapping effect, collective electron bunches can also

significantly alter the plasma field. Charged particles undergo an entirely different process of acceleration compared with that when the laser intensity is below 10^{22} W/cm² in the non-QED regime. In the near-QED regime, the stochastic RR effect will participate in the nonthermal acceleration of charged particles.

In this article, we have investigated the acceleration of electrons/protons by taking into account the stochastic QED effect in our simulation based on an ultraintense laser pulse with a peak intensity above 10^{23} W/cm². At such a high laser intensity, the radiation loss of electrons is inevitable, and the laser pulse depletes its energy to energetic electrons/protons as well as γ -photons. The nonthermal spectrum of produced electrons is also essentially a power-law distribution function, and its slope varies by approximately 1.5. The radiated γ -photons also have a broad energy spectrum extending up to 3 GeV when the normalized laser intensity $a_0 = 500$. Furthermore, the charge separation field modified by the RR effect accelerated the protons to 0.5 GeV and lead to a nonthermal spectrum with a power-law index of 0.7.

Result

Staged power-law spectrum of electrons

A relativistic laser pulse propagating in a near-critical density plasma ($0.1-10n_c$) induces a plasma channel along the propagation path of the laser pulse instead of a periodic structure wakefield. Both electrons and protons are accelerated inside the plasma channel. There are two simulations (please refer to Methods for specific parameters) with switching the on/off RR effect to study the acceleration process of charged particles in an intense laser field. As shown in Fig. 1, a clear plasma channel forms in both cases. Electrons are expelled away along the laser axis and transversal direction by strong pondermotive force, and a plasma channel forms after driving the laser pulse. As the RR effect is switched on, a great number of energetic electrons accumulate inside the plasma channel due to the RR trapping effect, as shown in Fig. 1(a). Protons also accumulate at the laser axis due to the transversal electric field, as plotted in Fig. 1(b), forming a dense quasi-neutral plasma beam²¹. As the laser pulse further propagates, both the electron and proton beam densities greatly increase over the critical density (see Fig. 1(d) and (e)). This trapped plasma bunch has a transverse size of 20 μm and longitudinal length of 50 μm , which is much longer than the laser pulse. The first half of the electron bunch overlaps with the laser pulse. They are directly accelerated and modulated by the intense laser field, resulting in a periodic distribution of electron density. These electrons oscillate in the laser field, emitting high-energy γ -photons. The production of a high-energy electron beam and γ -photon beam causes serious energy consumption of the local pulse field and thus leads to a blurry distribution of E_y at the back part of the laser pulse, as shown in Fig. 1(f). When the RR is turned off, the plasma channel is almost empty, and there are few electrons and protons inside the channel. Moreover, the laser energy loss is much smaller than that in the case of RR on, as plotted in Fig. 1(f) and (i). It is clear that the RR trapping effect greatly changes the electron density distribution and thus the acceleration process of charged particles bunching inside the plasma channel as well as the γ -photon beam production when the laser intensity is beyond 10^{23} W/cm².

The RR effect has a fundamental influence on the particle acceleration process when the RR force is comparable to the laser pondermotive force and traps electrons at the propagation axis of the laser pulse. Figure 2(a) presents the normalized energy spectrum of energetic electrons in different time steps as the laser intensity $a_0 = 500$. The maximum energy of electrons quickly increases beyond the GeV level and then stops at 5 GeV, leading to a broad energy spectrum. The energy spectrum has a nonthermal distribution function with a constant power-law slope of ~ 1.5 during the whole acceleration process. The electron spectrum in the RR-off case has a power-law index of ~ 2 , which agrees well with that in the non-QED regime⁸. At $t = 374 T_0$ in Fig. 2(b), the power-law index remains constant over the simulation time, but the cutoff energy of high-energy electrons extends beyond 10 GeV, which is much larger than that in the RR-on case. This confirms that the QED effect leads to a large drop in high-energy electrons because these high-energy electrons efficiently channel energy into the radiated γ -photon beam. The corresponding spectra for γ -photons with energy $E_\gamma > 1$ MeV are plotted in Fig. 2(c), which is synchrotron-like with maximal energy up to 3 GeV.

A series of simulations have been performed to study the electron acceleration with different laser intensities from $a_0 = 50$ to $a_0 = 1000$, where other laser and plasma parameters remain constant (see Methods). When the laser intensity of $a_0 = 50$ is far from the near-QED regime, the electron spectrum has a power-law distribution with an index of ~ 2 , as shown by the black dotted-dashed line in Fig. 3(a), which is similar to the previous result in the non-QED regime⁸. Both the energetic electron number and energy increase by one order of magnitude when the laser intensity increases to $a_0 = 100$, but the power-law index is still ~ 2 . As the laser intensity further increases above 10^{23} W/cm² ($a_0 = 400$ and 500), the maximum energy of electrons increases to 5 GeV with a sharp knee near the cutoff energy, and the power-law index of its spectrum decreases from ~ 2 to ~ 1.5 . The QED effect starts to play a significant role in the electron acceleration process and stops rapidly increasing the electron cutoff energy since energetic electrons emit a great number of γ -ray photons. This effect becomes clearer as the laser intensity further increases beyond 10^{24} W/cm². Both the electron energy and number have a small increase compared to $a_0 = 500$, as shown in Fig. 3(c), since a large part of the laser energy is depleted into high-energy γ -photons rather than energetic electrons. Thus, the power-law index of the electron spectrum further decreases to ~ 1.2 .

The maximum energy evolution of energetic electrons is present for different laser intensities in Fig. 4(a). In the case of $a_0 = 50$, the maximum electron energy increases rapidly beyond 1 GeV at $100 T_0$ and then slowly increases at approximately 3 GeV until the laser pulse field starts to decrease due to energy loss after $300 T_0$. When the laser intensity increases to $a_0 > 500$ in the near-QED regime, the maximum energy of accelerated electrons rapidly increases until $150 T_0$ and then remains constant, which is completely different from the non-QED regime. Electron energy stops increasing in the near-QED regime since electrons radiate a great number of gamma-ray photons during their acceleration process, which again confirms that QED effects strongly modulate the electron acceleration process. Figure 4(b) shows that the

maximum energy of electrons increases linearly with a_0 instead of a_0^2 and that the QED effect changes this trend.

Nonthermal Electron Accelerating Mechanism

The generation of an accelerated electron bunch with its spectrum of power-law distribution functions in an intense laser field has a large difference from that in the non-QED regime. These electrons undergo three main different acceleration mechanisms: direct laser acceleration (DLA), nonlinear multiphoton scattering and spatial charge-separation field acceleration, where the QED effect significantly contributes to the laser plasma interaction process.

Figure 5 presents the longitudinal electron density and electron momentum at $y = 0$ inside the plasma channel. The laser pulse occupied the range of $x = 230$ and $255 \mu\text{m}$, where a large number of electrons are accelerated via the strong pondermotive force of the intense laser field, i.e., the DLA mechanism. These energetic electrons have a high density spike above $10 n_c$ located $x = 256 \mu\text{m}$ in front of the plasma channel. DLA is an effective mechanism for accelerating electrons to several GeVs^{22,23}. The accelerated electrons have a periodic laser field structure. For electrons initially at rest, longitudinal and transversal momentum gains in the first half laser cycle are $p_y = a$ and $p_x = a^2/2$ and then turn to zero in the remaining half cycle. Electrons quiver frequently in the laser field and thus lead to stochastic emitting radiation as well as being trapped inside the plasma channel. A large part of the laser energy is converted into high-energy γ -photons. Thus, an electron accelerated by the DLA process of relativistic electrons is always accompanied by efficient γ -ray beam radiation.

In our simulations, the quantum discrete process in the PIC simulation is realized based on the Monte algorithm, and each radiation event is calculated within an optical depth according to the quantum probability²⁴. The most energetic photons are radiated at a certain angle of 0.22 rad along the laser propagation axis. Radiation processes exert transient RR force f_d in the opposite direction of photon emission to radiated electrons. When the laser intensity exceeds 10^{22} W/cm^2 , f_d is comparable to the laser pondermotive force and thus significantly participates in the electron acceleration process, bringing random electron trajectories. Each radiation event is accompanied by one multiphoton process, $e^- + n\gamma_L \rightarrow e^- + \gamma$, where γ_L and γ represent laser photons and γ -photons^{24,25}. This is a pure quantum phenomenon, and the quantity of f_d is exactly proportional $\hbar$. Thus, a radiating electron will suddenly change its momentum during γ -photon emission, which brings both random electron direction of motion and kinetic energy. Collective electron bunches that suffer stochastic effects will lead to exotic phenomena, e.g., energy spreading of electrons²⁷ and stochastic heating of electrons in a standing laser field^{28,29}. Electrons have a larger probability of emitting γ -photon radiation as their energy increases in the laser field. Thus, stochastic effects of quantum emission prevent the energy spectrum from high-energy expansion and induce bending of power-law spectra at approximately 2 GeV with laser

intensity above $a_0 = 500$ in Fig. 3(b), while the electron spectrum has no sharp end at the cutoff energy in the non-QED regime.

The RR trapping effect leads to both electron and proton accumulation inside the plasma channel as the laser intensity exceeds 10^{23} W/cm², forming a high-density plasma bunch, as shown in Fig. 1(a, b) and (d, e), and creates a large-amplitude charge-separation field. The longitudinal electric field E_x at $y = 0$, marked by the black solid line in Fig. 5(a), has both a positive field of 100 TV/m located between 230 μm and 255 μm for decelerating electrons (or accelerating protons) and a negative field of -25 TV/m at $x = 220$ μm for accelerating electrons (or decelerating protons). One notes that E_x lacks the periodic structure of the laser wakefield and is not sensitive to the plasma wavelength because the driving laser pulse has a much larger temporal and spatial scale than the plasma wavelength of $\lambda_p = 1.1$ μm under the condition of $n_e = 0.5 n_c$. A large number of electrons is accelerated/decelerated by the local charge-separation field. Their longitudinal momentum p_x reaches a peak value of 3000 at approximately 220 μm , as plotted in Fig. 5(b). Moreover, E_x is sensitive to the plasma bunch as well as the laser pulse evolution and thus leads to electrons participating in time-dependent acceleration and deceleration phases. These electrons cannot have continuous energy gain and bring a broad spectrum. However, the maximum momentum of these electrons is much lower than that of electrons accelerated in the DLA regime, which is above 9000 (see Fig. 5(b)).

Proton Acceleration In Near-qed Regime

For driving laser intensities lower than 10^{25} W/cm², a proton cannot be accelerated to relativistic energy within a short light period. The principle of proton acceleration in the plasma channel is similar to that of electrons accelerated by a wakefield, and they can be accelerated by a positive longitudinal electric field in front of the bubble channel^{30,31}. The RR trapping effect significantly alters the space-charge field distribution as the laser intensity reaches $a_0 = 500$ in our simulation. Longitudinal field E_x has a positive value of 100 TV/cm in the front part of the plasma channel, as plotted in Fig. 5 (a), where the proton bunch confined within the plasma channel can be mainly accelerated. However, the velocities of these protons at the end of the acceleration field are not high enough to catch up with the laser pulse and then move to the deceleration phase. Moreover, the accelerating space-charge field E_x inside the plasma channel changes over time with the plasma bunch and laser field, which also brings an unstable acceleration field. Thus, protons accelerated in the time-dependent charge-separation field also result in a nonthermal spectrum distribution, as shown in Fig. 6, instead of a quasi-monoenergetic spectrum.

The maximum energy gain for protons in the plasma channel is approximately $E_p \sim m_e c^2$, which is estimated based on the Coulomb electrostatic potential resulting in radial explosion in the non-QED regime²². For laser intensities of $a_0 = 50$ and 100, the maximal proton energies in our simulation are 23 MeV and 50 MeV, respectively, and agree well with the estimation of E_p . When the laser intensity increases to $a_0 = 1000$, the maximal proton energy is 5 GeV, which is larger than the E_p estimated by

more than one order of magnitude and almost catches up with the cutoff energy of electrons. Such high energy gain for protons mainly benefits from the longitudinal space-charge field, originally from electron trapping induced by the RR effect. Proton spectra with different laser intensities, as plotted in Fig. 6, show that the cutoff energy of accelerated protons strongly extends with increasing laser intensity. Additionally, the power-law index of the proton spectrum is ~ 1.5 in the case of $a_0 = 50$ and $a_0 = 100$. However, it decreases to 0.7 with a sudden decrease near the cutoff energy as the intensity increases above 10^{23} W/cm². The evolution of the proton energy spectrum with increasing laser intensity is similar to that of electrons. The ultraintense laser pulse drives a strong charge-separation field due to the RR effect, which accelerates protons to high energy and leads to a step-like power-law proton spectrum.

Discussion

The nonthermal acceleration process of electrons/protons by extending laser intensity into the near-QED regime has been studied in detail based on 2D PIC simulations. The accelerated electron energy spectra exhibit a nonthermal distribution function with a power-law index. The RR effect brings an inherent stochastic process for electron dynamics. γ -photon radiation from energetic electrons induces a step-like spectrum of electrons and prevents the electron spectrum from high-energy expansion beyond 10 GeV. The power-law slope decreases from 2 to 1.2 from $a_0 = 50$ to $a_0 = 1000$. Protons are mainly accelerated by the space-charge field modified by the RR effect in the plasma channel, and the spectra also show a nonthermal distribution with a slope of 0.7 in the near-QED regime. The nonthermal acceleration of charged particles in the near-QED regime is universal for the next generation of 10PW or even 100PW laser facilities and will help to explore the high-energy cosmic-ray acceleration mechanism in laboratory astrophysics.

Methods

We performed 2D simulations to study the acceleration process of charged particles by using an ultraintense laser pulse based on the Particle-In-Cell code Epoch³², where the RR effect was included here. The simulation window of size $x \times y = 90 \mu\text{m} \times 60 \mu\text{m}$ is divided into 1800×1200 cells, and each cell contains 30 macroparticles. A relativistic y -polarized laser pulse with a center wavelength of $\lambda_0 = 0.8 \mu\text{m}$ propagates along the x axis. It has Gaussian temporal-spatial profiles with $a(r, t) = a_0 \exp\left(-\left(r/w_0\right)^2\right) \exp\left(-2\ln 2\left(t/\tau_0\right)^2\right)$, where its focal size is $w_0 = 5\lambda_0$ and the pulse duration is $\tau_0 = 60\text{fs}$. Peak laser intensities of $a_0 = 500$ are used in our simulations, where a_0 is the normalized wave potential of the laser. The focus position is set at $x = 40 \mu\text{m}$. Background plasma is located between $20 \mu\text{m}$ and $400 \mu\text{m}$, where its density linearly increases from 0 to $n_e = 0.5n_c$ in the range of $20 - 40 \mu\text{m}$ and then remains constant at $n_e = 0.5n_c$ until $x = 400 \mu\text{m}$. Here, $n_c = m_e \omega_p^2 \epsilon_0 / e^2$ is the critical density, with m_e , ω_p and ϵ_0 being the mass of electrons, plasma frequency and permittivity of free space, respectively. The effects of electron-positron pair production are ignored here due to the quite low quantum efficiency.

Declarations

Data availability

All data generated and analyzed that support this work of study are available from the corresponding author on reasonable request.

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Author contributions

B.-F. S., Y. K. and H. T. conceived the idea and conducted the work. Y.-L. H. carried out all the simulations and analyzed the data. Y.-L. H and J.-C. X completed writing and revision of the manuscript. All authors agreed on this work.

Competing Interest Statement

The authors declare no competing interests.

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Figures

Figure 1

Simulation results for switching on/off RR effect. Density distributions of electrons (a) (d) (g), protons (b) (e) (h) and the laser field E_y (c) (f) (i) are present at time $t = 245 T_0$ and $t = 450 T_0$. The RR effect is turned on at (a)-(f) and turned off at (g)-(i). E_y is normalized to $E_0 = 1015 \text{ V/m}$. The laser intensity was $a_0 = 500$, and the plasma density was $n_e = 0.5 n_c$.

Figure 2

Time evolution of electron spectrum. As the RR is switched on (a) and off (b) as well as the γ -photon beam (c) at $t = 112 T_0$, $187 T_0$ and $374 T_0$ with laser intensities of $a_0 = 500$ and $n_e = 0.5$ nc.

Figure 3

Energy distribution function of accelerated electrons with different laser intensities. (a) $a_0 = 50, 100$, (b) $a_0 = 400, 500$ and (c) $a_0 = 800, 1000$. The power-law index decreases from ~ 2 to ~ 1.2 .

Figure 4

(a) Maximum energy evolution of accelerated electrons with time for different laser intensities. (b) The maximum energy that electrons reach at different laser intensities (data in the simulation are represented by red triangles, and the corresponding fitting results are represented by black lines.)

Figure 5

(a) Longitudinal electric field E_x (black solid line) and density distribution of electrons n_e/n_c (red dashed line) at $y = 0$. (b) Electron distribution at x - p_x phase plane.

Figure 6

Energy distribution function of proton. (a) $a_0 = 50, 100$, (b) $a_0 = 400, 500$ and (c) $a_0 = 800, 1000$. The power-law slope is ~ 1.5 for (a), ~ 0.7 for (b) and (c).