# Laser Field Absorption in Self-Generated Electron-Positron Pair Plasma

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Recently, much attention has been attracted to the problem of limitations on the attainable intensity of high power lasers [A. M. Fedotov *et al.*, Phys. Rev. Lett. **105**, 080402 (2010)]. The laser energy can be absorbed by electron-positron pair plasma produced from a seed by a strong laser field via the development of the electromagnetic cascades. The numerical model for a self-consistent study of electron-positron pair plasma dynamics is developed. Strong absorption of the laser energy in self-generated overdense electron-positron pair plasma is demonstrated. It is shown that the absorption becomes important for a not extremely high laser intensity $I \sim 10^{24}$ W/cm$^2$ achievable in the near future.

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Because of the impressive progress in laser technology, laser pulses with a peak intensity of nearly $2 \times 10^{22}$ W/cm$^2$ are now available in the laboratory [1]. When the matter is irradiated by such intense laser pulses, ultrarelativistic dense plasma can be produced. In addition to being of fundamental interest, such plasma is an efficient source of particles and radiation with extreme parameters that opens bright perspectives in the development of advanced particle accelerators [2], next generation of radiation sources [3,4], laboratory modeling of astrophysics phenomena [5], etc. Even higher laser intensities can be achieved with the coming large laser facilities like ELI (Extreme Light Infrastructure) [6] or HiPER (High Power laser Energy Research facility) [7]. At such intensity the radiation reaction and quantum electrodynamics (QED) effects become important [8–13].

One of the QED effects, which has recently attracted much attention, is the electron-positron pair plasma (EPPP) creation in a strong laser field [11,12]. The plasma can be produced via avalanchelike electromagnetic cascades: the seed charged particles are accelerated in the laser field, then they emit energetic photons, the photons by turn decay in the laser field and create electron-positron pairs. The arising electrons and positrons are accelerated in the laser field and produce new generation of the photons and pairs. It is predicted [12] that an essential part of the laser energy is spent on EPPP production and heating. This can limit the attainable intensity of high power lasers. That prediction was derived using simple estimates; therefore, a self-consistent treatment based on first principles is needed.

The collective dynamics of EPPP in a strong laser field is a very complex phenomenon and numerical modeling becomes important to explore EPPP. Up to now the numerical models for collective QED effects in strong laser field have not been self-consistent. One approach in numerical modeling is focused on plasma dynamics and neglects the QED processes such as pair production in the laser field. It is typically based on particle-in-cell (PIC) methods and uses an equation for particle motion with radiation reaction forces taken into account [13]. The second one is based on a Monte Carlo (MC) algorithm for photon emission and electron-positron pair production. This approach has been used to study the dynamics of electromagnetic cascades [14]. However, it completely ignores the self-generated fields of EPPP and the reverse effect of EPPP on the external field. The latter effect is especially important to determine the limitations on the intensity of high power lasers [12,15].

Quantum effects in strong electromagnetic fields can be characterized by the dimensionless invariants [16,17] $\chi_e = e\hbar/(m^3c^4)|F_{\mu\nu}p_\nu| \approx \gamma(F_\perp/eE_{\rm cr})$ and $\chi_\gamma \approx (\hbar\omega/mc^2) \times (F_\perp/eE_{\rm cr})$, where $F_{\mu\nu}$ is the field-strength tensor, $p_\mu$ is the particle four-momentum, $\hbar\omega$ is the photon energy, $\gamma$ is the electron gamma factor, $F_\perp$ is the component of Lorentz force, which is perpendicular to the electron velocity, $E_{\rm cr} = m^2c^3/(e\hbar) = 10^{16}$ V/cm is the so-called QED characteristic field, and $\hbar$ is the Planck constant. $\chi_e$ determines photon emission by relativistic electron while $\chi_\gamma$ determines interaction of hard photons with electromagnetic field. QED effects are important when $\chi_e \gtrsim 1$ or $\chi_\gamma \gtrsim 1$. If $\chi_e \gtrsim 1$, then $\hbar\omega \sim \gamma mc^2$ and the quantum recoil imposed on the electron by the emitted photon is strong. The probability rate of emission of a photon with energy $\hbar\omega$ by relativistic electron with gamma factor $\gamma$ can be written in the form [17–19]

 

$$dW_{\rm em}(\xi) = \frac{\alpha mc^2}{\sqrt{3}\pi\hbar\gamma}\Big[\Big(1-\xi+\frac{1}{1-\xi}\Big)K_{2/3}(\delta) - \int_\delta^\infty K_{1/3}(s)ds\Big]d\xi, \quad (1)$$

where $\hbar\omega$ is the photon energy, $m$ is the electron mass, $c$ is the speed of light, $\delta = 2\xi/[3(1-\xi)\chi_e]$, and $\xi = \hbar\omega/(\gamma mc^2)$. $\hbar\omega dW_{\rm em}$ can be considered as the energy distribution of the electron radiation power. For electron radiation in a constant magnetic field $\mathbf{B}$ perpendicular to the electron velocity, it reduces to the synchrotron radiation spectrum in the classical limit $\chi_e \ll 1$ [18,20]. The probability rate of electron-positron pair production by decay of a photon with energy $\hbar\omega$ is [17–19]

$$dW_{\rm pair}(\eta_-) = \frac{\alpha m^2c^4}{\sqrt{3}\pi\hbar^2\omega}\Big[\Big(\frac{\eta_+}{\eta_-}+\frac{\eta_-}{\eta_+}\Big)K_{2/3}(\delta) - \int_\delta^\infty K_{1/3}(s)ds\Big]d\eta, \quad (2)$$

where $\delta = 2/(3\chi_\gamma\eta_-\eta_+)$, $\eta_- = \gamma mc^2/(\hbar\omega)$, and $\eta_+ = 1-\eta_-$ are the normalized electron and positron energies, respectively. It follows from Eq. (2) that in the classical limit $\chi_\gamma \ll 1$ this probability is exponentially small.

To study EPPP dynamics we have developed a two-dimensional numerical model based on PIC-MC methods. Similar methods have been used previously for modeling of discharges in gases [21]. Recently a one-dimensional PIC-MC model has been developed to simulate pair cascades in a magnetosphere of neutron stars [22]. However, the latter model is electrostatic, and the classical approach is used for photon emission with a radiation reaction force in the equation of motion. In our numerical model we use a more general approach. We exploit the fact that there is a large difference between the photon energy scales in EPPP. The photon energy of the laser and plasma fields is low ($\hbar\omega \ll mc^2$) while the energy of the photons emitted by accelerated electrons and positrons is very high ($\hbar\omega \gg mc^2$). The emitted photons are hard and can be treated as particles. Conversely, the evolution of the laser and plasma fields is calculated by numerical solution of the Maxwell equations. Therefore, the dynamics of electrons, positrons, and hard photons, as well as the evolution of the plasma and laser fields, are calculated by the PIC technique while emission of hard photons and pair production are calculated by the MC method.

The photon emission is modeled as follows. On every time step for each electron and positron we sample a photon emission by a probability distribution which approximates Eq. (1) with accuracy within 5%. The new photon is included in the simulation region. The coordinates of a new photon are equal to the electron (positron) coordinates at the emission instance. The photon momentum is parallel to the electron (positron) momentum. The electron (positron) momentum value is decreased by the value of the photon momentum. A similar algorithm is used for modeling of pair production by photons. The new electron and positron are added in the simulation region while the photon that produced a pair is removed. The sum of the electron and positron energy is equal to the photon energy. The pair velocity is directed along the photon velocity at the instant of creation.

The MC part of our numerical model has been benchmarked to simulations performed by other MC codes. We simulated the electromagnetic showers in a static homogeneous magnetic field, the interaction of a relativistic electron beam with a strong laser pulse, and the development of electromagnetic cascades in circularly polarized laser pulses. The obtained results are in reasonably good agreement with those published by other authors and are discussed in Ref. [19]. The particle motion and evolution of the electromagnetic field are calculated with a standard PIC technique [23]. The PIC part of the model is a two-dimensional version of the model used in Ref. [24]. In order to prevent memory overflow during simulation because of the exponential growth of particle number in a cascade, the method of particles merging is used [22]. If the number of the particles becomes too large, the randomly selected particles are deleted while the charge, mass, and energy of the rest particles are increased by the charge, mass, and energy of the deleted particles, respectively.

We use our numerical model to study production and dynamics of EPPP in the field of two colliding linearly polarized laser pulses. The laser pulses have Gaussian envelopes and propagate along the $x$ axis. The components of the laser field at $t = 0$ are $E_y, B_z = a_0 \exp(-y^2/\sigma_r^2) \times \sin\zeta[e^{-(x+x_0)^2/\sigma_x^2} \pm e^{-(x-x_0)^2/\sigma_x^2}]$, where the field strengths are normalized to $mc\omega_L/|e|$, the coordinates are normalized to $c/\omega_L$, time is normalized to $1/\omega_L$, $a_0 = |e|E_0/(mc\omega_L)$, $E_0$ is the electric field amplitude of a single laser pulse, $\omega_L$ is the laser pulse cyclic frequency, $2x_0$ is the initial distance between the laser pulses, $\zeta = x - \phi$, and $\phi$ is the phase shift. The parameters of our simulations are $\phi = 0.8\pi$, $a_0 = 1.2 \times 10^3$, $\sigma_x = 125$, $\sigma_r = 40$, $x_0 = \sigma_x/2$ that for the wavelength $\lambda = 2\pi c/\omega_L = 0.8$ $\mu$m correspond to the intensity $3 \times 10^{24}$ W/cm$^2$, pulse duration 100 fs, the focal spot size 10 $\mu$m at $1/e^2$ intensity level. The cascade is initiated by a single electron located at $x = y = 0$ with zero initial momentum for $t = 0$ when the laser pulses approach each other (the distance between the pulse centers is $\sigma_x$).

The later stage ($t = 25.5\lambda/c$) of the cascade development is shown in Fig. 1, where the electron and photon density distributions and the laser intensity distribution are presented. The laser pulses passed through each other by this time instance and the distance between the pulse centers becomes about $1.6\sigma_x$. It is seen from Fig. 1 that the micron-size cluster of overdense EPPP is produced and the laser energy at the backs of the incident laser pulses is spent on EPPP production and heating. The plasma density exceeds the relativistic critical density $a_0 n_{\rm cr} \simeq 10^{24}$ cm$^{-3}$ in about 2 times, where $n_{\rm cr} = m\omega^2/(8\pi e^2)$ is the

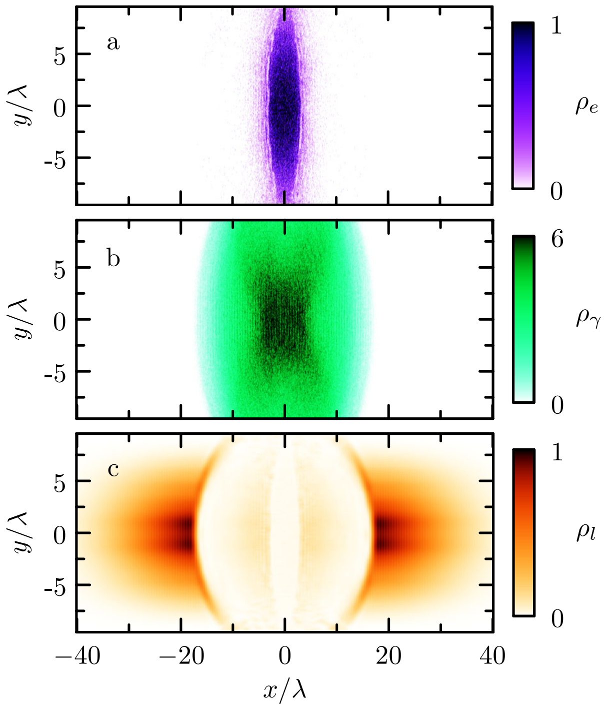


FIG. 1 (color online). The normalized electron density $\rho_e = n_e/(a_0 n_{\rm cr})$ (a), the normalized photon density $\rho_\gamma = n_\gamma/(a_0 n_{\rm cr})$ (b), and the laser intensity normalized to the maximum of the initial intensity $\rho_l$ (c) during the collision of two linearly polarized laser pulses at $t = 25.5\lambda/c$. The density distribution of positrons is approximately the same as that of electrons.

nonrelativistic critical density for the electron-positron plasma. The evolution of the particle and laser energy is shown in Fig. 2. It is seen from Fig. 2 that about half of the laser energy is absorbed by self-generated EPPP and then mostly reradiated in an ultrashort pulse of gamma quanta. The total energy of the particles in the cascade and the electromagnetic field is conserved with accuracy of about 1% during our simulation.

At the initial stage of the cascade development, the number of created particles is growing exponentially $N \sim e^{\Gamma t}$ [12], where $\Gamma$ is the multiplication rate. It follows from the energy conservation law that the number of particles that can be created is limited by the laser pulse energy. Thus, at some instant the exponential growth is replaced by much slower growth. Equating the initial energy of laser pulses to the overall particle energy after the pulse collision, we get $N \sim a_0^2 \sigma_x \sigma_r^2 N_0/\bar{\gamma}$, where we assume $N_e \sim N_p \sim N_{\rm ph} \sim N$, where $N_e$, $N_p$, and $N_{\rm ph}$ are the number of electrons, positrons, and photons produced by the cascade, respectively, $mc^2\bar{\gamma}$ is the average particle energy, $N_0 = n_{\rm cr}(c/\omega)^3 = \lambda/(16\pi r_e)$, $r_e = e^2/(mc^2)$. The multiplication rate decreases when the field strength goes down, which, in turn, occurs if the plasma density reaches the value $a_0 n_{\rm cr}$. This is in good agreement with the numerical results shown in Fig. 3, where the multiplication rate drops dramatically and EPPP density reaches the value about $a_0 n_{\rm cr}$ at the same instant of time $t_s \approx 10\lambda/c$. The value of $t_s$ can be estimated as $t_s \approx \Gamma^{-1} \ln N$. It follows from Fig. 3 that $\Gamma \approx 0.6\omega_L$ for $t < t_s$. The typical lifetime $t_{\rm em}$ for electrons and positrons with respect to hard photon emission can be estimated as $1/\Gamma > 1/\omega_L$ [12]. Thus, for the parameters of numerical simulation, $\bar{\gamma}$ can be estimated as $\bar{\gamma} \sim a_0$; hence, $N \sim a_0 \sigma_x \sigma_r^2 N_0 \sim 4 \times 10^{14}$ and $ct_s/\lambda \sim 9$, which are in good agreement with the corresponding values from Fig. 3.

It is shown in Ref. [15] that the cascades do not arise in the $B$ node of a linearly polarized standing electromagnetic wave as long as $\chi_e$ and $\chi_\gamma$ are less than unity. However, our numerical simulations show that the cascade quasiperiodically develops between $B$ and $E$ nodes of such a wave. This is because under such conditions the electron motion becomes complicated and is not confined to the direction of polarization on the temporal scales around the laser period. It turns out that there occur the time intervals of duration of

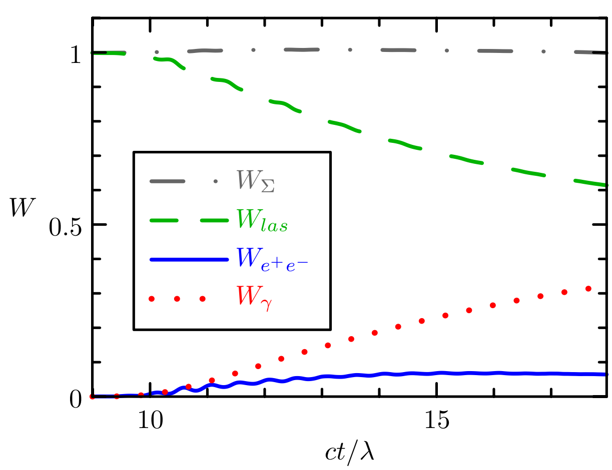


FIG. 2 (color online). The electron and positron energy (solid line), the photon energy (dotted line), the laser energy (dashed line), and the total energy of the system (dash-dotted line) as functions of time. All the energies are normalized to the initial energy of the system.

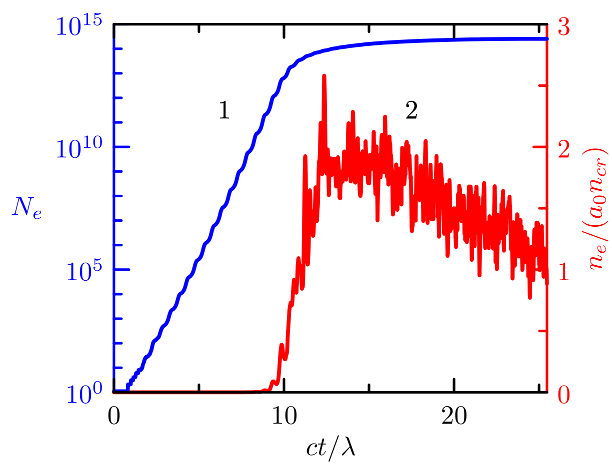


FIG. 3 (color online). The number of the electrons produced in the cascade (line 1) and the EPPP density normalized to the relativistic critical density (line 2) as functions of time.

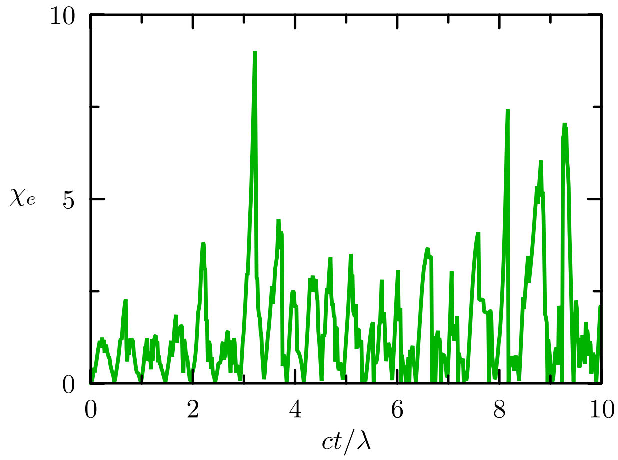


FIG. 4 (color online). The dependence of $\chi_e$ for the primary electron on time.

the order of $\omega_L^{-1}$ with $\chi_e > 1$ (see Fig. 5) on which the cascade can develop. The time modulations of $N_e(t)$ and of EPPP density along the $x$ axis at the initial stage of the cascade development are seen in Figs. 3 and 4, respectively. At the later stages the spatial modulation of the density is strongly smoothed out due to EPPP expansion (see Fig. 4, line 2).

In conclusion we have developed the numerical model which allows us to study EPPP dynamics in a strong laser field self-consistently. We have demonstrated efficient production of EPPP at the cost of the energy of the laser pulses. We show that even not extremely high intensity laser pulses ($I \sim 10^{24}$ W/cm$^2$ with duration $\sim$100 fs) can produce overdense EPPP so that the QED effects can be experimentally studied with soon-coming laser facilities like ELI [6] and HiPER [7]. The simulations and estimates show that for intensity $I > 10^{26}$ W/cm$^2$ the overdense EPPP can be produced during a single laser period. In such a high-intensity regime few-cycle laser pulses can be used in experiments. High-energy photons or an electron-positron pair instead of an electron can also be used as a seed to initiate cascade. Photon-initiated cascade can be more suitable for experimental study in the low intensity regime ($I \sim 10^{24}$ W/cm$^2$) because the laser intensity threshold for pair creation in vacuum is about $\sim 10^{26}$ W/cm$^2$ [25].

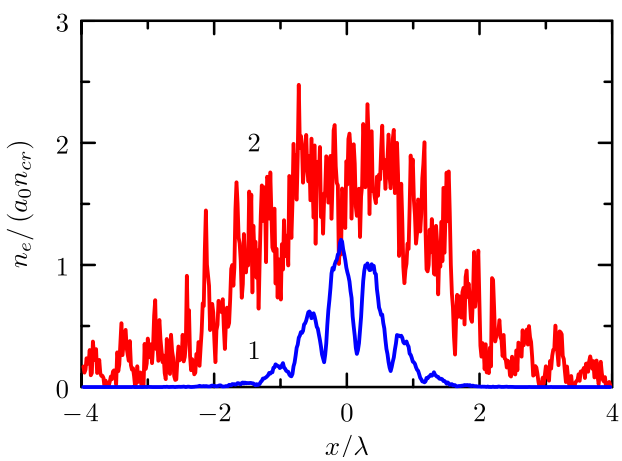


FIG. 5 (color online). The profile of the electron density along the $x$ axis at $y = 0$ for initial stage $ct = 6.4\lambda$ (line 1) and for the later stage $ct = 16.6\lambda$ (line 2) of the cascade development. The electron density for $ct = 16.6\lambda$ is normalized to $a_0 n_{\rm cr}$, and that for $ct = 6.4\lambda$ is normalized to $3.3 \times 10^{-6} a_0 n_{\rm cr}$.

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[1] V. Yanovsky *et al.*, Opt. Express **16**, 2109 (2008).
[2] E. Esarey *et al.*, Rev. Mod. Phys. **81**, 1229 (2009).
[3] S. Kiselev, A. Pukhov, and I. Kostyukov, Phys. Rev. Lett. **93**, 135004 (2004).
[4] A. Rousse *et al.*, Phys. Rev. Lett. **93**, 135005 (2004).
[5] B. A. Remington, R. P. Drake, and D. D. Ryutov, Rev. Mod. Phys. **78**, 755 (2006).
[6] http://www.extreme-light-infrastructure.eu.
[7] http://www.hiper-laser.org.
[8] T. Tajima and G. Mourou, Phys. Rev. ST Accel. Beams **5**, 031301 (2002).
[9] G. A. Mourou, T. Tajima, and S. V. Bulanov, Rev. Mod. Phys. **78**, 309 (2006).
[10] E. Nerush and I. Kostyukov, Phys. Rev. E **75**, 057401 (2007).
[11] A. R. Bell and J. G. Kirk, Phys. Rev. Lett. **101**, 200403 (2008).
[12] A. M. Fedotov *et al.*, Phys. Rev. Lett. **105**, 080402 (2010).
[13] I. V. Sokolov *et al.*, Phys. Rev. E **81**, 036412 (2010).
[14] V. Anguelov and H. Vankov, J. Phys. G **25**, 1755 (1999).
[15] S. S. Bulanov *et al.*, Phys. Rev. Lett. **105**, 220407 (2010).
[16] A. I. Nikishov and V. I. Ritus Zh. Eksp. Teor. Fiz. **46**, 776 (1964) [Sov. Phys. JETP **19**, 529 (1964)].
[17] V. B. Berestetskii, E. M. Lifshits, and L. P. Pitaevskii, *Quantum Electrodynamics* (Pergamon, New York, 1982).
[18] V. N. Baier, V. M. Katkov, and V. M. Strakhovenko, *Electromagnetic Processes at High Energies in Oriented Single Crystals* (World Scientific, Singapore, 1998).
[19] N. V. Elkina *et al.* arXiv:1010.4528.
[20] L. D. Landau and E. M. Lifshits, *The Classical Theory of Fields* (Pergamon, New York, 1982).
[21] V. A. Shklyaev and V. V. Ryzhov, Tech. Phys. Lett. **35**, 518 (2009).
[22] A. N. Timokhin, Mon. Not. R. Astron. Soc. **408**, 2092 (2010).
[23] A. Pukhov, J. Plasma Phys. **61**, 425 (1999).
[24] E. N. Nerush and I. Yu. Kostyukov, Phys. Rev. Lett. **103**, 035001 (2009).
[25] N. B. Narozhny *et al.*, Zh. Eksp. Teor. Fiz. **129**, 14 (2006) [JETP **102**, 9 (2006)].