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Phys. Rev. A **103**, 053114 — Published 19 May 2021

DOI: 10.1103/PhysRevA.103.053114

Reaching the high laser intensity by a radiating electron

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The question whether an electron radiating its energy away during the interaction with a laser can reach the region of highest intensity with energy high enough to make a number of different phenomena observable is one of the most studied and most important in the Strong Field Quantum Electrodynamics. Here a simple analytical estimate for an average electron energy evolution is proposed and benchmarked against particle-in-cell simulations. Furthermore, these results are used to estimate the electron and laser pulse properties required to make vacuum Cherenkov emission observable.

One of the interaction geometries employed to study the strong field Quantum Electrodynamics (SF QED) is the collision of a high energy electron beam and an intense electromagnetic (EM) pulse [1–7]. With the increase of laser intensities [8–12] as well as the energies of laser-accelerated electrons [13], the utilization of them both turned into a standard setup for the study of radiation reaction (RR), both classical and quantum, which starts to dominate electron energy loss through photon emission (Compton process). The photons being exposed to the strong EM fields right after the emission can transform into electron-positron pairs through the Breit-Wheeler process [2, 14]. Since the rate of this transformation depends on both photon energy and field strength, which in their turn depend on how far an electron penetrated into the region of strong fields in the laser pulse, the understanding of electron energy depletion due to photon emission is of paramount importance. This issue has been extensively studied recently (see e.g. Refs. [15–19]). One of the interesting results of these studies is the dependence of energy depletion and pair production rates on the temporal and spatial EM field dimensions, *i.e.*, reducing the field-particle interaction time to a minimum prevents a particle from radiating and thus it would allow probing the fully nonperturbative QED regime [20–26].

When optical laser intensities reach above 10^{23} W/cm^2, the QED effects in the laser-electron collision can significantly alter the electron dynamics affecting the energy spread and the divergence of the electron beam [27–30]. Further increase of both laser intensity and electron beam energy will lead to Cherenkov radiation which is caused by the vacuum polarization effect [31–36] and will approach the regime where the semi-perturbative expansion of the SF QED supposedly breaks down [20–25, 37]. We note, that solely the collision of the ultra-intense laser beam with another laser beam [38] or gamma photons [39] will lead to the experimental evidence of vacuum polarization effect.

The strong fields mentioned above are those that either approach or exceed the critical field of QED, $E_{\mathrm{S}} = m_e^2c^3/e\hbar \approx 1.33\times10^{16}$ V/cm with corresponding intensity of the order of 10^{29} W/cm^2. Here m_e denotes the electron mass, c speed of light, e is the elementary charge and $\hbar$ is the reduced Planck constant. However, to achieve such a field strength with a laser, one needs the power of $\mathcal{P} \sim (\lambda\,[\mu m])^2$ ZW provided that the laser pulse is focused to a λ spot-size. The corresponding energy of a single cycle laser is $\mathcal{E} \sim 3\,(\lambda\,[\mu m])^3$ MJ. The available now lasers can generate intensities exceeding 10^{22} W/cm^2, next generation of lasers is expected to achieve $10^{23} - 10^{25}$ W/cm^2. However, the energy requirements might become prohibitive for further advancement of laser technology. Therefore the reduction of the laser wavelength might be a way for relaxing power and energy requirements to achieve high intensities. There are several possible paths to generate ultra-short laser pulses focusable to intensities 10^{25} W/cm^2, which have been proposed or are conceptually possible by extrapolating the existing laser technology. These include using self-phase modulation of a broadband multi-petawatt laser pulses in a structured solid medium [40], prospects for generation of ultra-high contrast second harmonic fs pulses at 400 nm in a Ti:sapphire system [41] or at 527 nm from high-energy Nd:glass kJ beams [42] by ultrathin frequency converters, prospects for generation of a ≈ 530 nm, < 20 fs pulses by OPCPA in a large-aperture LBO amplifier driven by third harmonics of a 1 μm pump laser [43, 44]. Another technique for shortening the laser wavelength is to exploit the non-linear properties of the laser-produced plasma. This is represented by the concept of relativistic flying plasma mirrors [45, 46].

We note that thresholds of different regimes of charged particle interaction with strong EM fields depend on both field strength and laser wavelength (see [37] for details). However, many of these thresholds are derived using single Compton and Breit-Wheeler processes, whereas the interaction in such strong fields usually involves multiple photon emissions and pair productions. Thus, a simple qualitative estimate is needed for charged particle energy evolution during such interaction, which would allow to understand whether the conditions for reaching a specific regime or process are met.

In what follows we consider the interaction of 10–100s GeV electrons with short EM pulses of intensity 10^{23-25} W/cm^2. We show, that the electron energy loss at specific locations in the colliding laser pulse can be easily obtained by a simple analytical formula based on the geometrical correspondence between the flat-top and the Gaussian temporal envelopes of the laser pulse having the same total energy. The analysis is performed for different frequencies and durations of the laser light and the provided analytical expressions are in excellent agreement with the numerical simulations. These findings might be useful for estimating the conditions for observing QED effects in laser-electron collisions at future laser facilities, especially those which require the electron of specific energy experiencing the field in the laser pulse center. As an example, we utilize these estimates to find the laser parameters, which would allow the observation of the Cherenkov radiation in the laser-electron collision through the modification of the distribution of Breit-Wheeler positrons due to the vacuum polarization.

In QED the interaction of charged particles (electrons and positrons) and photons with EM field is characterized by two Lorentz invariant parameters, $\chi_e = \sqrt{-\left(F^{\mu\nu}p_\nu\right)^2}/m_e c E_{\rm S}$ and $\chi_\gamma = \hbar\sqrt{-\left(F^{\mu\nu}k_\nu\right)^2}/m_e c E_{\rm S}$, where $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$ is the EM field tensor, A_ν is the four-potential, p_ν is the four-momentum of the electron, and k_ν is the photon four-wave vector. The strength of the EM field is characterized by the Lorentz invariant parameter $a_0 = eE_0/m_e\omega_0 c$, where E_0 is the amplitude of the electric field and ω_0 is the laser frequency. We assume a head-on collision of an electron having the initial energy $\mathcal{E}_e = \gamma_e m_e c^2$, where $\gamma_e \gg 1$ is the relativistic Lorentz factor, with a linearly polarized plane wave characterized by the peak intensity I_0, the wavelength λ and the full width at half maximum duration τ in laser intensity. In this case, the maximum value of parameter χ_e can be approximately expressed as $2\gamma_e E_0/E_{\rm S}$.

In the limit of a large χ_e parameter ($\chi_e \gg 1$), i.e. in the quantum RR regime, the rate of single-photon emission per unit time for the Compton process is given by $W_\gamma \approx 3^{2/3} 28\Gamma\left(2/3\right)\alpha m_e^2 c^4 \chi_e^{2/3}/54\hbar\mathcal{E}_e$, where $\Gamma\left(x\right)$ is the Gamma function and $\alpha = e^2/\hbar c$ is the fine structure constant. As a result of a photon emission an electron losses 16/63 of its initial energy on average [32].

In order to estimate an electron energy loss, we assume that the electron travels towards the high-intensity region of the laser pulse. The electron emits Compton photons according to the rate W_γ. Each emission leads to the above-mentioned electron energy loss. Further we assume that the electron always emits one photon when $W_\gamma \Delta t = 1$, where Δt is the time of radiation. To adapt W_γ for a laser pulse with a Gaussian temporal envelope characterized by the peak intensity I_0 and the duration τ, we need to consider a laser pulse with a flat-top temporal envelope having the duration $2\tau/\sqrt{2\ln 2}$ providing the same energy as the Gaussian one. The time required for an electron to reach the center of the top-hat laser pulse is $\tau/\sqrt{2\ln 2}$.

Photon emission rate depends on the phase $\psi = \omega_0 t$ of the laser field as $\sin\psi$. For a single laser cycle, the rate is the highest twice per a laser period T when the intensity $I \propto \sin^2\psi$ reaches its local maxima at $\psi = \pi/2$ and $\psi = 3\pi/2$. Therefore, we assume that photon emission can happen when $\sin^2\psi \geq 1/2$ and thus the effective time interval for photon emission by the moment when the electron reaches the center of the laser pulse is $t_{\rm c} \approx \tau/2\sqrt{2\ln 2}$. During the time interval $t_{\rm c}$, multiple emission of photons may occur. Since the number of emitted photons can be estimated as $p_{\rm c} \approx W_\gamma t_{\rm c}$, the electron reaches the center of the laser pulse with the energy given by

$$\mathcal{E}_e^{\rm c} \approx \left(1 - 16/63\right)^{p_{\rm c}} \mathcal{E}_e. \tag{1}$$

Then the average $\chi_e^{\rm c}$ of the electron in the presence of the laser field center can be directly obtained as $\chi_e^{\rm c} \approx 2\gamma_e^{\rm c} E_0/E_{\rm S}$, where $\gamma_e^{\rm c}$ is the relativistic Lorentz factor of the electron in the center of the laser pulse. The final electron energy after passing through the laser pulse is $\mathcal{E}_e^{\rm f} \approx \left(1 - 16/63\right)^{p_{\rm f}} \mathcal{E}_e$, where $p_{\rm f} \approx W_\gamma t_{\rm f}$ and $t_{\rm f} \approx \tau/\sqrt{2\ln 2}$.

We assume that the electron has initially enough energy to reach the center of the laser pulse. However, even when RR is not considered, the electron can be prevented from experiencing the laser field maximum due to the ponderomotive force if $\gamma_e < \sqrt{1 + a_0^2/2}$. When RR comes into play, then the electron with $\gamma_e \gg \sqrt{1 + a_0^2/2}$ can lose a significant fraction of its energy as it propagates towards the laser pulse center. The condition for electron reflection therefore depends on the ponderomotive potential barrier and the actual energy of the radiating electron. As a result, the electron can be expelled by the ponderomotive force before reaching the center of the laser pulse. In the limit $\chi_e \gg 1$, we estimate, using the above-presented approach, the threshold for reflection of the radiating electron as

$$\mathcal{E}_e^{\rm r}/m_e c^2 \approx \sqrt{1 + a_0^2/2}, \tag{2}$$

where $\mathcal{E}_e^{\rm r} \approx \left(1 - 16/63\right)^{p_{\rm r}} \mathcal{E}_e$, $p_{\rm r} \approx W_\gamma t_{\rm r}$ and $t_{\rm r} \approx t_{\rm c}/\sqrt{2}\left(\sqrt{2\ln 2}\right)^{\tau/T-1}$ that accounts for the conversion between the Gaussian and the flat-top laser pulse. We note, however, that the consideration of the electron reflection can not be achieved in the framework of an adopted 1D model. In the case when the condition (2) becomes relevant, the transverse momentum of electron becomes of the order of longitudinal one and full 3D dynamics of the electron should be taken into account.

Having written down the estimates for the average electron energies in the center of the pulse and after the interaction, we compare them with the results of 1D Particle-In-Cell (PIC) simulations performed by the code SMILEI

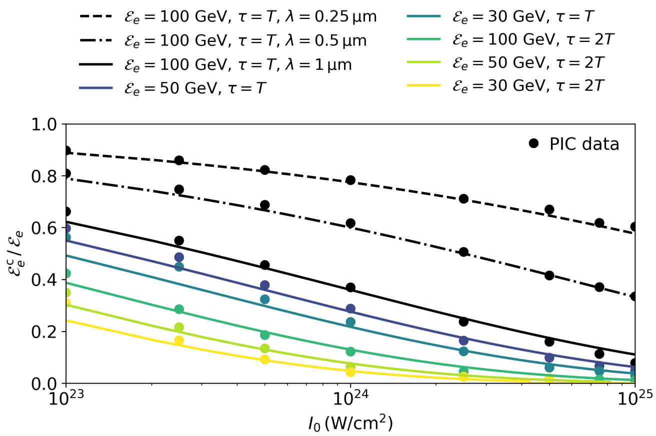

FIG. 1. Electron energy $\mathcal{E}_e^c$ in the center of the laser pulse as a function of laser intensity I_0 predicted by Eq. (1) (lines) and obtained from PIC simulations (bullets). The laser pulse characterized by the duration τ and the wavelength λ collides head-on with electrons of the initial energy $\mathcal{E}_e$. Solid lines represent cases with $\lambda = 1$ μm.

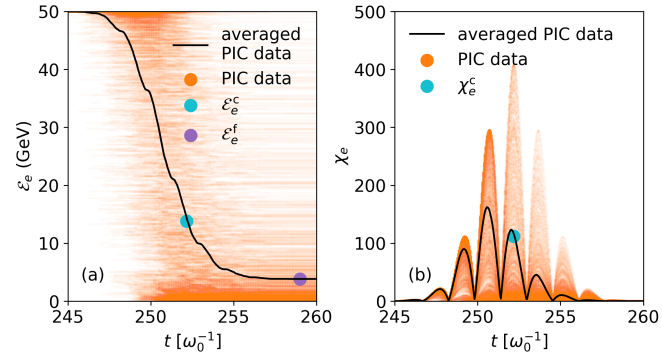

FIG. 2. Comparison of PIC data (orange) and their averaged value (black line) with theoretical estimates of electron energy (a) in the center of the laser pulse $\mathcal{E}_e^c$ and after passing the laser pulse $\mathcal{E}_e^f$. (b) Time evolution of χ_e and the estimated value χ_e^c in the center of the laser pulse. The laser pulse characterized by the intensity $I_0 = 10^{24}$ W/cm^2, the wavelength $\lambda = 1$ μm and the duration $\tau = T$ collides head-on with an electron of the initial energy $\mathcal{E}_e = 50$ GeV.

[47]. In the code, photon emission and electron-positron pair creation are modelled using Monte-Carlo approach. We use a linearly polarized plane wave with a Gaussian temporal envelope τ having the peak intensity I_0 in the range 10^{23-25} W/cm^2 and the wavelengths $\lambda = 0.25$ μm, 0.5 μm and 1 μm. Such a laser pulse collides head-on with 10^5 simulation electrons of initial energy $\mathcal{E}_e$.

In Fig. 1 we present the results for electron energy in the center of the laser pulse. The theoretical predictions are compared with simulation data for two different durations of the laser pulse and three values of the initial electron energy (solid lines). It is shown, that increasing the initial electron energy or shortening the laser pulse duration results in a reduction of the energy emitted before the electron enters the center of the laser pulse. The first aspect is given by the fact that in the limit $\chi_e \gg 1$, the rate of photon emission $W_\gamma \propto \gamma_e^{-1/3}$. The latter is caused by a linear dependence of the emitted photon number on the interaction duration. Dash-dotted and dashed lines show that shortening the laser wavelength can further reduce the amount of emitted energy before the electron reaches the center of a single cycle laser pulse.

Due to the stochastic nature of photon emission in the QED regime of interaction, the colliding electrons lose a various fraction of their energy at different times. This can be seen in Fig. 2(a) showing the simulation data of electron energy distribution as a function of time for the electron of the initial energy $\mathcal{E}_e = 50$ GeV interacting with a laser pulse characterized by $I = 10^{24}$ W/cm^2, $\lambda = 1$ μm and $\tau = T$. However, the general trend of the electron energy evolution is illustrated by the black solid line obtained by the averaging of the PIC results. Its value in the center of the laser pulse and after the interaction is in good agreement with theoretical estimations $\mathcal{E}_e^c$ and $\mathcal{E}_e^f$, respectively. In panel (b) we show the distribution of parameter χ_e during the interaction as obtained from PIC simulation. As can be seen, its average value (black line) is considerably affected by RR making it not symmetric around its peak value [1]. However, the value in the center of the laser pulse corresponds with the predicted χ_e^c. Note the maximum value of the averaged χ_e parameter is achieved before reaching the laser pulse center.

In the laser-electron collision, only electrons of sufficiently high energy can overcome the ponderomotive barrier created by the amplitude of the intense laser pulse. Using PIC code, we have performed a set of simulations for different combinations of $\mathcal{E}_e$ and τ to find the threshold intensity I_0^{PIC} at which the electrons are reflected. As shown in Fig. 3, the obtained data are in good agreement with the threshold intensity I_0^{theory} estimated by Eq. (2).

The presented approach may help to find the optimal condition for laser-matter interaction in which the electron of the required energy is assumed to experience the field at the laser pulse center. One example is the emission of the Cherenkov photons in the laser-electron collision [31–36]. The strong EM field of the laser pulse changes the vacuum index of refraction, and thus the colliding electron propagating with the super-luminal phase velocity can emit the Cherenkov photons. For observing the Cherenkov radiation in such a collision, the minimum required Lorentz factor of the electron experiencing the laser pulse center is given by $\gamma_{\min} = 1/\sqrt{2\Delta n}$, where $\Delta n = n - 1$ is the induced change in the index of refraction for a probe photon having $0 < \chi_\gamma \lesssim 15$ [31, 33]. While Δn has a maximum at $\chi_\gamma \approx 5$, for $\chi_\gamma \gtrsim 15$ the value of Δn becomes negative and thus the Cherenkov radiation vanishes [31, 33, 35]. In the limit $\chi_\gamma \ll 1$, $\Delta n = 8\alpha E_0^2/45\pi E_S^2$ [31].

The Cherenkov photons can only be emitted if the electron in the center of the laser pulse satisfies $\gamma_e^c \geq \gamma_{\min}$.

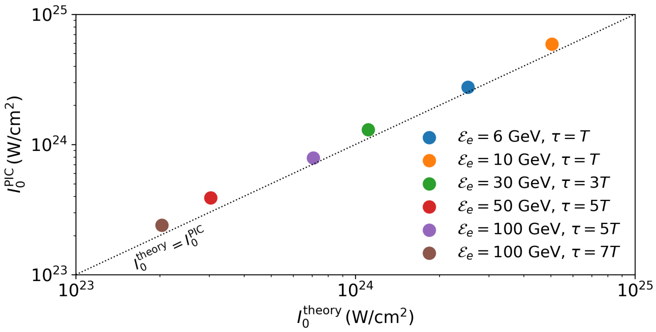

FIG. 3. Threshold intensity required for electron reflection by the laser pulse predicted by the theory I_0^{theory} given by Eq. (2) (x-axis), and obtained from PIC simulations I_0^{PIC} (bullets) for different values of the initial electron energy $\mathcal{E}_e$ and the laser pulse duration τ. The laser wavelength is $\lambda = 1$ μm. The dotted line is added to guide the eye for $I_0^{\mathrm{theory}} = I_0^{\mathrm{PIC}}$.

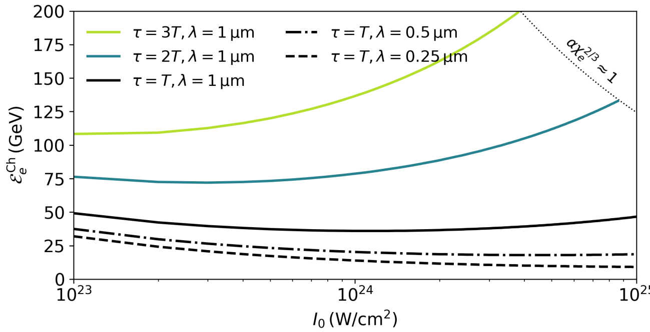

FIG. 4. The minimum required initial electron energy $\mathcal{E}_e^{\mathrm{Ch}}$ for the emission of the Cherenkov radiation in the center of the laser pulse of intensity I_0, duration τ and wavelength λ obtained by Eq. (1) for $\gamma_e^{\mathrm{c}} = \gamma_{\min}$ in the limit $\chi_\gamma \ll 1$.

By inserting $\gamma_e^{\mathrm{c}} = \gamma_{\min}$ into Eq. (1), we can estimate what would be then the required minimum initial energy $\mathcal{E}_e^{\mathrm{Ch}}$ of such an electron. In Fig. 4 we present the required initial energy of the electron for the emission of the Cherenkov radiation in the center of the laser pulse for $\chi_\gamma \ll 1$. It is shown, that using both the short wavelength and the short laser duration efficiently reduces the energy threshold. For example, to achieve the Cherenkov radiation at near-future laser system characterized by intensity $I_0 = 10^{24}$ W/cm^2 and pulse duration $\tau = T$, the electron beam of initial energy $\mathcal{E}_e^{\mathrm{Ch}} \approx 14$ GeV is required assuming the wavelength $\lambda = 0.25$ μm. This provides more than two times lower requirement on the initial electron energy compared to the case of 1 μm laser wavelength. The presented calculations were performed within the regime where the perturbation theory can be applied, i.e. where $\alpha\chi_e^{2/3} \leq 1$.

It has been shown that photons emitted via the Cherenkov and Compton mechanisms have different angular distributions [35]. However, the evidence of the Cherenkov radiation in photon spectra of laser-electron collision for $\chi_\gamma \ll 1$ seems to be unnoticeable in the region of perturbative QED [34, 36]. Nevertheless, the presence of the Cherenkov photons in the laser-electron collision can be indicated by the creation of Breit-Wheeler positrons provided that the photon energy is sufficiently high. If the Cherenkov radiation is present, the total number of Breit-Wheeler positrons should be higher than expected from solely Compton radiation. Therefore, we consider the Cherenkov radiation for $\chi_\gamma \approx 1$ as this represents an optimal regime for SF QED effects [1, 31, 32]. Using the above-mentioned approach, one can identify the lowest electron initial energy for a given laser intensity and duration in order to reach $\chi_\gamma \approx 1$ for the Cherenkov photons within the limit of perturbative QED. For $\chi_\gamma \approx 1$ we obtain $\Delta n \approx 2\alpha E_0^2/E_{\mathrm{S}}^2$ [32], and, thus, for example, the required minimum initial electron energy for emitting the Cherenkov photons characterized by $\chi_\gamma \approx 1$ is $\mathcal{E}_e^{\mathrm{Ch}} \approx 20$ GeV considering $I_0 = 10^{25}$ W/cm^2, $\lambda = 1$ μm and $\tau = T$. Such a photon carries out $\chi_\gamma/\chi_e \approx 1/12$ of the electron energy when radiated in the center of the laser pulse. One can compare the importance of the Cherenkov and the Compton radiation of such photons. The emitted power by a photon with $\chi_\gamma \approx 1$ is $P_{\mathrm{Ch}} = \alpha^2 m_e^2 c^4 \left(1 + 1/\alpha\chi_e^2\right)/\hbar$ for the Cherenkov and $P_{\mathrm{C}} = \sqrt{3}\alpha m_e^2 c^4 F\left(\chi_e, \chi_\gamma\right)/2\pi\hbar$ for the Compton radiation, where $F\left(\chi_e, \chi_\gamma\right)$ is the quantum-corrected synchrotron spectrum function [32]. For the above-mentioned parameters we obtain $P_{\mathrm{Ch}} \approx 0.15 P_{\mathrm{C}}$. The average formation time for pair production by such a photon is on the order of $\sim 4\hbar E_{\mathrm{S}}/\alpha m_e c^2 E_0$ i.e. $\sim 10^{-2}T$ [32]. Provided that these Cherenkov photons create pairs at the same rate as the Compton ones, the total number of positrons with the average initial energy $\mathcal{E}_e^{\mathrm{c}}/24 \approx 20$ MeV (assuming pair production rate has a maximum at producing electron and positron with equal energy for this value of χ_γ) should be higher by 15% compared to the case when only Compton radiation is considered. These positrons should be created within the cone of opening angle $\theta_{\mathrm{Ch}} \approx 2\sqrt{4\alpha\left(E_0/E_{\mathrm{S}}\right)^2 + \left(m_e c^2/\mathcal{E}_e^{\mathrm{c}}\right)^2} \approx 3 \times 10^{-3}$, see Fig. 5 [32]. This might serve as an indication of the vacuum polarization effect presence in a laser-electron collision as pair annihilation in a background laser field has a negligible effect on QED cascades [48].

In conclusion, using the simple analytical approach we estimate the average electron energy in the center of the counter-propagating intense EM wave in the limit $\chi_e \gg 1$ as well as the condition for electron reflection. The results show that reaching the center of the multi-PW laser pulse is attainable with 10-100s GeV electron even when radiation reaction is considered. The roles of laser pulse duration and laser wavelength on reaching the laser pulse center are quantitatively assessed and are in good agreement with the simulations. The conditions for the radiating electron to experience with the desired energy the amplitude of the counter-propagating strong electromagnetic wave are provided. Such knowledge is an essential step towards observing signatures of the non-linear quantum electrodynamics vacuum properties stemming

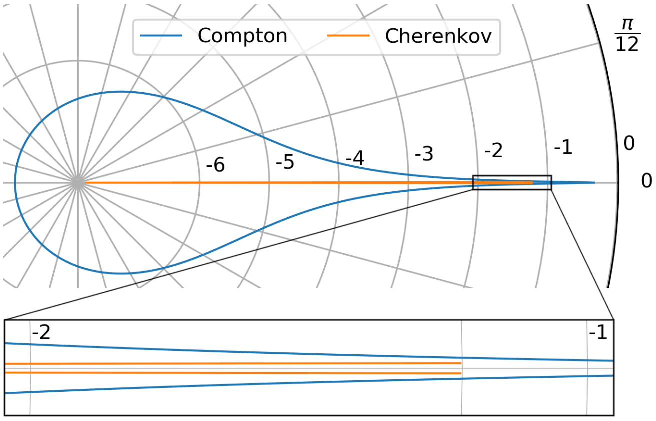

FIG. 5. The angular energy distribution $\log_{10}[E_\gamma\,(\mathrm{GeV})]$ of Compton photons (blue) emitted by the electron with the initial energy $\mathcal{E}_e^{\mathrm{Ch}} = 20$ GeV in the center of the laser pulse of parameters $I_0 = 10^{25}$ W/cm^2, $\lambda = 1$ μm, $\tau = T$. Cherenkov photons characterized by $\chi_\gamma \approx 1$ are emitted by this electron within the opening angle $\theta_{\mathrm{Ch}} \approx 3 \times 10^{-3}$ (orange).

from vacuum polarization in high-intensity laser-electron experiments, e.g. generation of Cherenkov radiation imprinting the signature of vacuum polarization in the distribution of Breit-Wheeler positrons.

Portions of this research were carried out at ELI Beamlines, a European user facility operated by the Institute of Physics of the Academy of Sciences of the Czech Republic. This work is supported by the project High Field Initiative (HIFI) CZ.02.1.01/0.0/0.0/15_003/0000449 from European Regional Development Fund (ERDF). SSB acknowledges support from the U.S. Department of Energy Office of Science Offices of High Energy Physics and Fusion Energy Sciences (through LaserNetUS), under Contract No. DE-AC02-05CH11231. This work was supported by The Ministry of Education, Youth and Sports from the Large Infrastructures for Research, Experimental Development and Innovations project "IT4Innovations National Supercomputing Center LM2018140". Computational resources were supplied by the project "e-Infrastruktura CZ" (e-INFRA LM2018140) provided within the program Projects of Large Research, Development and Innovations Infrastructures. The simulations were performed at the cluster ECLIPSE at ELI Beamlines.

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