

Radiatively trapped $e^\pm$ pair plasma as a laser-to- γ photon converter

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An energy equilibrium arises when an electron-positron pair plasma is generated by the nonlinear Breit-Wheeler interaction of a γ -ray bunch with laser photons and becomes radiatively confined. Ordinarily, ponderomotive scattering prevents leptons from accessing the high-field regions where quantum electrodynamics (QED) effects dominate, but if quantum (stochastic) radiation reaction is sufficiently strong, a balance of acceleration and recoil forces emerges. This unique scenario enables leptons to continuously mediate the transformation of laser photons into directed γ -rays via inverse Compton scattering as they copropagate with the field. Importantly, it is observed that the lepton energy stabilizes while the γ energy increases in direct proportion to laser energy depletion. The proposed scheme enables fundamental tests of QED, and is investigated here using the particle-in-cell method in full dimensionality, in addition to test-particle calculations. The per-species energy conversion efficiency is analyzed as a function of the initial laser and γ -beam properties.

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I. INTRODUCTION

A relativistic electron in a strong laser field can radiate a sizable fraction of its energy within a Compton wavelength $\lambda_c = \hbar/mc$ [1–4]. The energy gained $eE_0\lambda_c$ in the laser field of strength E_0 is given in units of the photon energy $\hbar\omega$ by the dimensionless, Lorentz-invariant field parameter $a_0 = eE_0/\omega mc$. An amplitude of $a_0 \simeq 200$, corresponding to a power of 10 PW and a record-breaking peak intensity of 10^{23} W/cm², has been attained at laser facilities such as ELI-NP [5] and CoReLS [6], with several other multipetawatt laser development projects underway to standardize such intensity levels and reach the next order of magnitude [7–12].

In the ultrahigh intensity regime, charged particle motion is altered by quantum electrodynamics (QED) effects such as nonlinear Compton scattering ($e^-(p) + n\omega \rightarrow e^-(p') + \gamma$) [13–19] and radiation reaction [20–27], which result in the emission of energetic γ -ray photons. Further, it becomes probable to create electron-positron ($e^\pm$) pairs from the interaction of a γ -photon with multiple laser photons by the nonlinear Breit-Wheeler process ($\gamma + n\omega \rightarrow e^\pm$) [28–36] (Feynman diagrams are provided in Fig. 1). A QED-dominated pair plasma arises from the cascade of successive γ - $e^\pm$ emission according to the aforementioned processes [37–42]. Typically, a field strength near to the Sauter-Schwinger value $E_S = m^2c^3/(e\hbar) \approx 1.32 \times 10^{18}$ V/m [37] is required to induce such effects. However, the Lorentz invariance of the theory implies that processes depend on the field in the particle's rest frame, which is enhanced by the relativistic factor.

The particle-in-cell (PIC) method for kinetic plasma modeling has been extended to account for quantum electrodynamics effects [43–46]. This is accomplished through a Monte Carlo treatment whereby the PIC macroparticles evolve classically between stochastic, quantum emission events. Probabilities for the various QED processes are readily evaluated using the Furry dressed-state representation [47] in which the high-order absorption of laser photons is implicitly accounted for through the field-dressed Volkov states [48] upon which particle generation is then treated perturbatively. The first-order generation processes depend on the so-called quantum parameters [49–51],

$$\chi_{e,\gamma} = \frac{\sqrt{-(F_{\mu\nu}p^\nu)^2}}{E_S mc} = \frac{1}{E_S mc} \left[\left(\frac{\varepsilon}{c} \mathbf{E} + \mathbf{p} \times \mathbf{B} \right)^2 - (\mathbf{p} \cdot \mathbf{E})^2 \right]^{1/2} \quad (1)$$

defined for leptons/photons (e/γ), where $p^\nu = (\varepsilon/c, \mathbf{p})$ ($= \hbar k^\nu$) is the lepton (photon) four-momentum, and $F_{\mu\nu}$ is the total field tensor, with electric and magnetic fields $\mathbf{E}$ and $\mathbf{B}$, at the position of the generating particle. A large χ_e value, on the order of unity, implies a high probability of photon emission, and similarly for χ_γ with respect to pair production.

In this work, we analyze and report a scenario in which a pair plasma is efficiently generated and radiatively trapped following the collision between an ultrarelativistic laser pulse and a seed γ -ray bunch. The interaction is illustrated in Fig. 2, which shows a transverse section of a 3D QED-PIC calculation based on the TURBOWAVE code [52]. The primary observation is that a quasiguiding equilibrium is established due to a balance between ponderomotive scattering and radiation friction that causes the generated leptons to access and remain within the high-field regions. As the leptons copropagate with the laser field, they mediate the conversion of laser photons into forward-directed γ -rays. This process continues until the field is distorted by the axial pair-plasma current,

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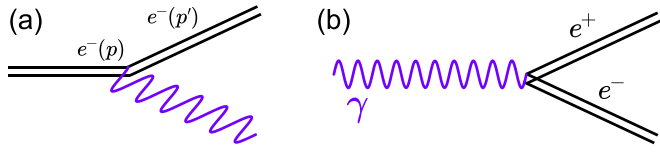


FIG. 1. Feynman diagram for (a) nonlinear Compton scattering and (b) nonlinear Breit-Wheeler pair creation. Double propagator lines represent laser-dressed fermions.

which leads to a decrease in the quantum parameters χ_e and consequently the photon emission rate.

Radiation-reaction trapping was studied by Ji *et al.* [53] in the context of laser-foil interaction, where a comparatively low density of plasma electrons were drawn into the ablation zone. Generally, electrons of a beam or plasma target exposed to an ultraintense laser pulse do not penetrate into the high-field region as effectively [54]. The laser- γ -beam configuration investigated in this work allows lepton generation directly within the high-field region where QED effects of interest are enhanced. This may enable fundamental tests of non-perturbative QED where quantum parameter values well in excess of unity are ideal. An equilibrium is observed in the energy dynamics [Fig. 3(a)] that is distinct from the “ γ -flash” energy burst of laser-foil interactions [45,53,55–57]. The trapped lepton density is an order of magnitude greater than the case involving plasma electrons accelerated from rest (see Ref. [53]), but this is dependent on the γ -beam properties, which provides a degree of control.

The majority of numerical QED-PIC studies [45,53,55–59] have considered near-infrared wavelengths of 0.8–1 μm common to available PW-class laser systems. However, scaling laws suggest that for fixed laser energy, shorter wavelengths are optimal for QED processes [60,61]. Although it is not widely appreciated, excimer lasers are capable of ultrashort pulse, high peak power operation. To date, an ArF amplifier has demonstrated 237 J, 107 ns pulses at 5 Hz [62,63] (see also Ref. [64] for KrF), and its conversion to ~ 30 fs, PW-class operation has been analyzed. By going to shorter wavelengths, tighter focusing also allows higher peak intensities for a given pulse energy. In the main calculation of this work, the wavelength is 193 nm, which corresponds

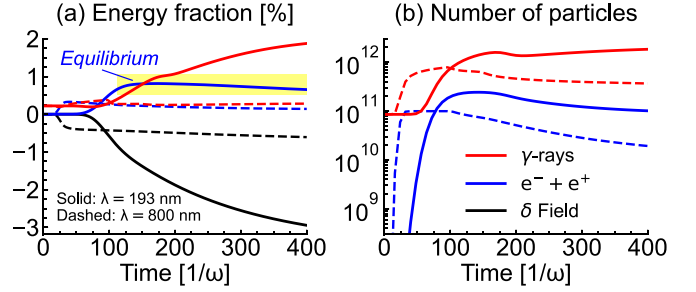


FIG. 3. (a) Total energy and (b) particle number vs time for each species, based on laser wavelengths of 193 nm (solid) and 800 nm (dashed); refer to details in the text. The electron and positron data are added together, and the ‘ δ Field’ curve signifies the laser energy minus its initial value.

to an ArF gain medium. The calculation has been repeated with a 0.8- μm -wavelength field of equal power and energy, and the laser-to- γ energy conversion efficiency in that case was less by a factor of ~ 6 [see Fig. 3(a)]. However, the radiative trapping effect is not exclusive to short wavelengths [34,53,54,65,66].

The remainder of this article is organized as follows. In Sec. II, we begin by detailing the QED-PIC calculation parameters and provide results of the particle dynamics and energy/momentum distributions (Sec. II B). A brief review of classical versus quantum radiation-reaction theory (Sec. II C) is accompanied by test-particle calculation results based on the Lorentz force law with radiation damping included (Sec. II D). The energy conversion efficiency as a function of laser field amplitude and γ -particle-beam properties is also presented (Sec. II D). In Sec. III, we summarize and conclude this work.

II. RESULTS

A. Calculation parameters

The main calculation results correspond to the case of Fig. 2. The laser field consists of a $\lambda = 193$ nm wavelength (ArF), $\tau = 30$ fs pulse of amplitude $a_0 = 500$ (9.18×10^{24} W/cm²). It is linearly polarized in $\hat{x}$ and has a transverse waist of $r_0 = 5\lambda$. The seed γ energies are 255 ± 5 MeV and

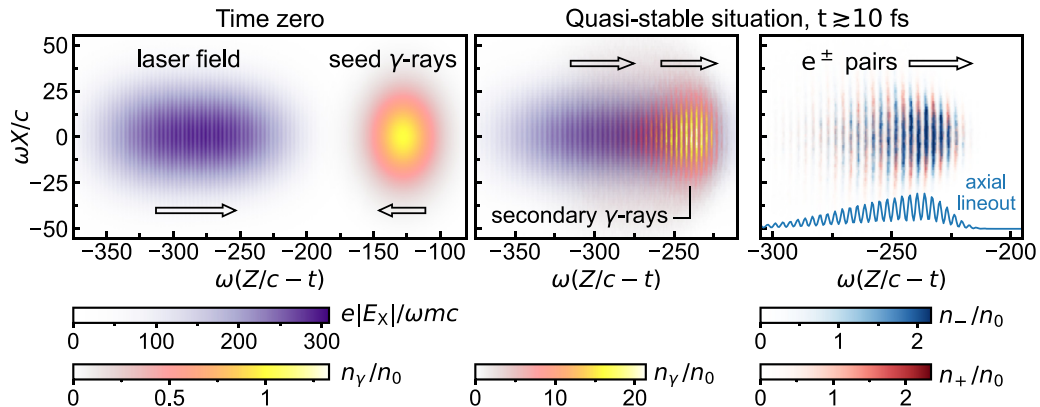


FIG. 2. The laser pulse collides head-on with a seed γ bunch, and $e^\pm$ pairs are generated. The majority of leptons are subsequently reversed by the field and they radiate γ 's in the forward direction, which leads to their radiative confinement.

the bunch is a 0.8- μm radius Gaussian sphere with a peak density of $n_0 = m\omega^2/4\pi e^2 \approx 3 \times 10^{22} \text{ cm}^{-3}$. (In this context, it is not physically significant that n_0 is the critical density associated with 193 nm light.)

One may consider the seed γ -rays to arise from an external inverse Compton scattering source, albeit with lesser energy and density than simulated here. For instance, the High Intensity γ -Ray Source (HI γ S) [67–69] is presently capable of delivering up to 100 MeV photons, with $3 \times 10^{10} \text{ } \gamma/\text{s}$ flux at 10 MeV and sub-ns pulse durations (N.B. shorter pulses are likely needed). Another possibility is the laser-plasma-waveguide scheme [59], which yielded $\sim 10^8$ photons at 250 MeV. In the following calculation, the seed photons were created with idealized properties in order to analyze the salient features of the interaction.

The computational domain consists of $128(x) \times 128(y) \times 2200(z)$ points with initially eight macroparticles per cell, where the density equals n_0 , and the spatial resolution is $\Delta x, \Delta y = 1.5/k$, $\Delta z = 0.2/k$, where $k = 2\pi/\lambda$ is the wavenumber. The calculation timestep in the laboratory frame must be less than the inverse maximum photon emission rate [46]: $\Delta t < \Gamma_{\text{max}}^{-1} (\approx 10^{-17} \text{ s in this case})$, where $\Gamma_{\text{max}} = (\sqrt{3}\alpha c/\pi\hbar c)h_0 \text{Max}[E, B]/E_S$ and $h_0 = 5.24$. The special unitary pusher [70], with higher-order timestep estimate, was employed due to its accuracy over the *de facto* Boris pusher [71] for relativistic particles. Convergence tests were also performed with the Higuera-Cary relativistic pusher [72] with comparable results. Finally, a 6 MeV cutoff energy for photon emission was set in order to prevent photons with low pair creation probabilities from overflowing the simulation, and convergence tests indicate that the dynamical behavior is not altered significantly if the cutoff value is reduced. Macroparticle merging techniques include those developed in Refs. [73–75], but were not utilized here.

B. Calculation results

In Fig. 3(a), the total energy fraction of each species, normalized to the initial laser pulse energy of 1.6 kJ [76], is plotted as a function of time. In the early stage of the laser- γ -beam interaction, the γ energy decreases as $e^\pm$ pairs are generated. Shortly thereafter, the lepton energy stabilizes as they continuously absorb laser photons and emit secondary γ -rays via nonlinear Compton scattering. This causes the γ energy fraction to rise sharply, in this case by $\sim 1.7\%$ over approximately 30 fs.

Figure 3(b) shows the time evolution of total particle numbers. There is an order-of-magnitude increase in the number of photons satisfying $\varepsilon_\gamma \geq 6 \text{ MeV}$. Moreover, Fig. 2 shows a time instant when the secondary γ density is $n_{\gamma, \text{max}}/n_0 \approx 23$, which is a significant increase from the seed density of n_0 . By the final calculation timestep, the peak densities are $n_{\gamma, \text{max}}/n_0 \approx 29$ and $n_{\pm, \text{max}}/n_0 \approx 2$. Based on the energy and density, the $e^\pm$ pairs constitute a plasma.

From Fig. 3(a), it is evident that if the pair plasma becomes radiatively trapped by the field, then it acts as a mediator of laser-to- γ photon energy. As verified by calculation, in the absence of radiative trapping, the leptons are rapidly expelled by the ponderomotive force, and the total γ energy simply decays. Based on observations of particle density vs time, and

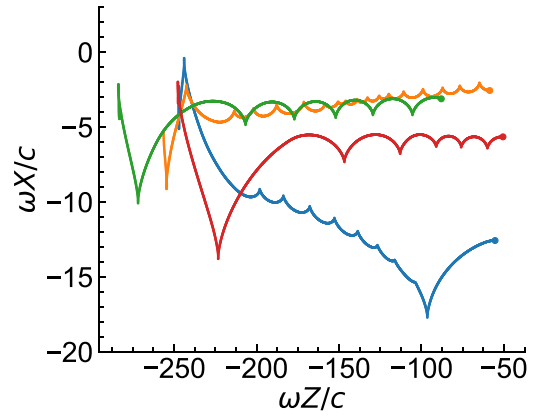


FIG. 4. Representative trajectories of radiatively guided electrons in the QED-PIC calculation. (Note: The beam is centered about $r_\perp = 0$ with a waist of $\omega r_0/c \simeq \pm 31.42$.)

as will become apparent from parameter scan data to follow, it was found that the radiative trapping mechanism depends critically on a_0 , and specifically the laser field's ability to reverse the lepton momenta that are counterpropagating at birth. A few representative electron orbits are provided in Fig. 4. The trapped leptons exhibit initially large transverse displacements, after which they settle into oscillatory motion near to the propagation axis. Trajectory analysis confirms that there is no continuous loss of trapping accompanied by the generation of new leptons.

The energy distribution [Fig. 5(a)] indicates that the generated leptons are highly energetic, with 45% and 80% of

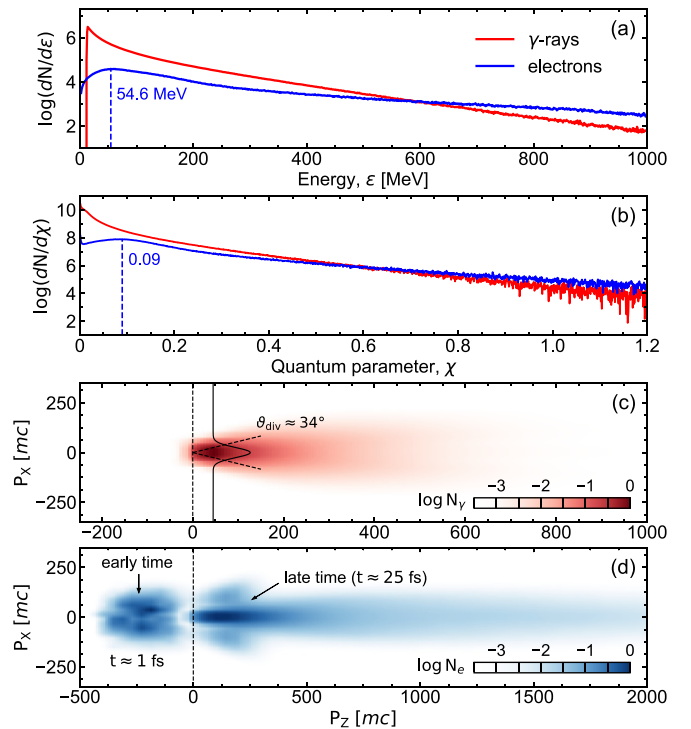


FIG. 5. Distribution functions of (a) energy, (b) quantum parameter, and (c) photon/(d) electron momenta, all corresponding to $t \approx 25 \text{ fs}$. Note: $dN/d\varepsilon$ and $dN/d\chi$ are normalized to total particle number.

the electron population contained within $\varepsilon \leq 100$ MeV and $\varepsilon \leq 250$ MeV, respectively. Moreover, the electron quantum parameter distribution [Fig. 5(b)] attains its maximum for $\chi_e^* = 0.09$, and 57% of the electron population has $\chi_e \geq \chi_e^*$.

Figures 5(c) and 5(d), respectively, show the photon and electron momentum distributions. The early-time, counter-propagating electrons are broadly distributed in momentum both axially and transversely, with the maximum occupation having $p_z^* \approx -200 mc$. The asymmetry in the early-time electron momentum distribution is due to the carrier-envelope phase of the laser pulse and the stochastic nature of particle production. Over time, some leptons are scattered away by the field, but those that become radiatively trapped and acquire $p_z > 0$ momenta are primarily on-axis, where the field amplitude is maximal. The electron momentum distribution of Fig. 5(d) exhibits a jetlike structure. By symmetry of the Breit-Wheeler process, the energy and momentum distributions of the positrons are nearly identical to those of the electrons.

The secondary radiation is emitted within a cone angle of $\Delta\vartheta \sim 1/\gamma_\ell$ about the lepton momentum, where $\gamma_\ell = [1 + (\mathbf{p}/mc)^2]^{1/2}$ is the relativistic factor [77]. In this scenario, because the $e^\pm$ pairs are ultrarelativistic and copropagating with the field, they emit γ -rays that are directional. Moreover, the generated γ -beam has a single lobe, in contrast to the two-lobe beams observed in laser-plasma-target interactions [53,56–58]. From Fig. 5(c), the secondary γ distribution is peaked on-axis ($\vartheta = 0^\circ$). At the point of maximum occupation, $p_z^* = 45 mc$, the distribution is approximately Gaussian in p_x with a half width at half maximum of $30 mc$. By this measure, the γ beam has a divergence angle of $\vartheta_{\text{div}} = \arctan(30/45) \approx 34^\circ$.

C. Radiation-reaction theory

The radiative confinement of $e^\pm$ pairs is a large- χ_e effect and therefore requires a quantum electrodynamical description. The average quantum radiation-reaction (RR) force experienced by a lepton of energy ε_e is given by [1]

$$\mathbf{F}_{\text{RR}}^{\text{Q}} = - \int d\varepsilon_\gamma \frac{dw}{d\varepsilon_\gamma} p_\gamma \hat{\mathbf{p}}_e, \quad (2)$$

where

$$\frac{dw}{d\varepsilon_\gamma} = - \frac{\alpha m^2 c^4}{\hbar \varepsilon_e^2} \left[\int_x^\infty d\xi \text{Ai}(\xi) + \left(\frac{2}{x} + \chi_\gamma \sqrt{x} \right) \text{Ai}'(x) \right]$$

is the differential-energy photon emission probability rate, ε_γ is the photon energy, $\chi_e' = \chi_e - \chi_\gamma$ is the final lepton quantum parameter, $\text{Ai}(\xi)$ is the Airy function, $\text{Ai}'(x)$ its derivative, and $x = (\chi_\gamma/\chi_e \chi_e')^{2/3}$. In the PIC calculations, the RR force is stochastic as opposed to averaged [46]. In the event of photon emission, the lepton momentum is immediately changed to conserve momentum, $\mathbf{p}'_e = \mathbf{p}_e - \hbar \mathbf{k}_\gamma$. In light of this stochastic behavior, it is surprising that lepton trapping is maintained consistently throughout the interaction.

We briefly remark that in the classical limit, the RR force derives from a different probability rate function $dw/d\varepsilon_\gamma$ that is implicitly dependent on χ_e (see Ref. [77], §74). However, it is well approximated by the χ_e -quadratic form [38]:

$$\mathbf{F}_{\text{RR}}^{\text{C}} \approx - \frac{2\alpha mc^3}{3 \lambda_c \varepsilon_e} \mathbf{p}_e \chi_e^2. \quad (3)$$

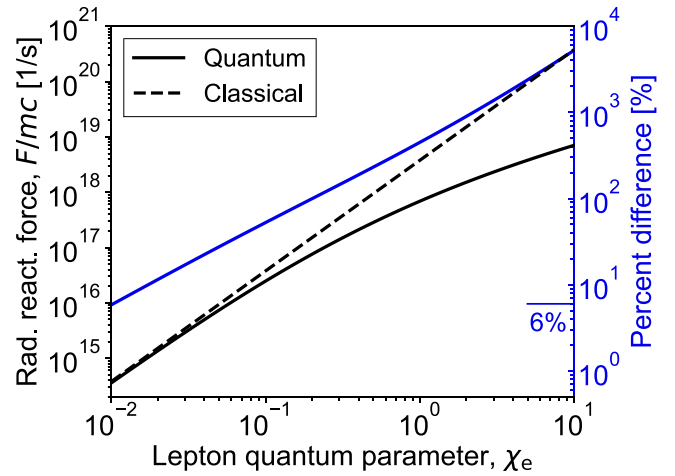


FIG. 6. Radiation-reaction force magnitude in quantum [Eq. (2)] (solid) vs classical [Eq. (3)] (dashed) theory, and the associated percent difference (solid blue).

Equations (2) and (3) both assume that the radiation is emitted in $\hat{\mathbf{p}}_e$, which is justified in the ultrarelativistic limit when the emission cone angle is infinitesimal. It is known that the classical theory overestimates the effect of radiation friction for increasingly large values of χ_e [1]. Trajectory-based signatures to distinguish between the quantum and classical RR regimes have been analyzed [78].

In Fig. 6, the RR force magnitudes according to quantum and classical theory are plotted as functions of χ_e . Here, it is apparent that classical theory overestimates the effect of radiation friction for increasingly large values of χ_e . In the regime of interest, $\chi_e \approx 0.1 - 1$, the difference between F_{RR}^{Q} and F_{RR}^{C} increases from 53% to 450%.

D. Test-particle calculations

The motion of a single lepton interacting with the laser field is determined by the relativistic Lorentz equation modified by the quantum RR force,

$$\frac{d\mathbf{p}}{dt} = \mathbf{F}_L + \mathbf{F}_{\text{RR}}^{\text{Q}}, \quad \mathbf{F}_L = \mp e(\mathbf{E} + \boldsymbol{\beta} \times \mathbf{B}), \quad (4)$$

where $\mathbf{p} = \gamma_\ell m \mathbf{v}$ and $\boldsymbol{\beta} = \mathbf{v}/c$. In the absence of RR, the average axial drift velocity due to the ponderomotive force is $\langle \beta_z \rangle = (a_0^2/2)/(2 + a_0^2/2)$ [79–82]. The threshold field amplitude to reverse a counterpropagating lepton with velocity β_0 is given by $a_0 = 2\sqrt{2}|\beta_0|/(1 - |\beta_0|) \approx 4\sqrt{2}\gamma_\ell^2$, for $\gamma_\ell \gg 1$. However, the effect of radiation friction is to lower this requirement by depleting some of the lepton energy, which can be seen from numerical integrations of Eq. (4). To this end, the laser electric field function was taken to be $E_x(\mathbf{r}, t) = E_0 \exp[-(t - z/c)^2/\tau^2] \cos(\pi x/2r_0) \cos(\pi y/2r_0) \cos(\omega t - kz)$ and $E_z(\mathbf{r}, t) = 0$, with the remaining components derived to satisfy Maxwell's equations in vacuum, and $\mathbf{E} = \mathbf{B} = \mathbf{0}$ for $|x|, |y| \geq r_0$. The laser parameters were taken to be identical to those in the QED-PIC calculation.

Test electrons were initialized at the laser pulse maximum ($z_0 = 0$) with different momenta $p_{z,0} = -mc(\gamma_{\ell,0}^2 - 1)^{1/2}$ and evolved independently according to Eq. (4), with $\mathbf{F}_{\text{RR}}^{\text{Q}}$

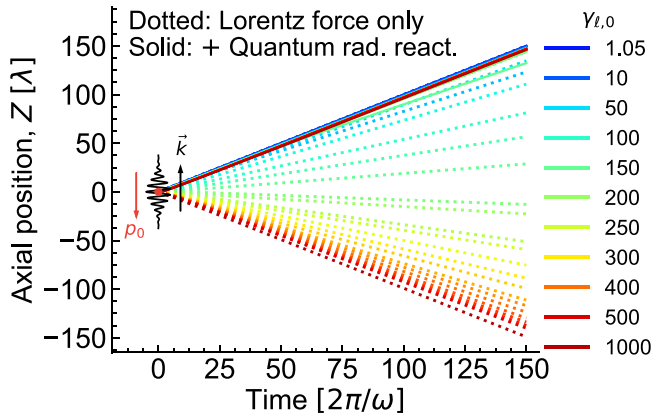


FIG. 7. Trajectories of test electrons with various relativistic factors $\gamma_{\ell,0}$ initially counterpropagating to a laser pulse, with/without (solid/dotted) quantum recoil accounted for. All of the trajectories with radiation reaction included (solid lines) are reversed by the laser pulse regardless of initial momentum.

accounted for by numerically sampling Eq. (2) and interpolating based on the χ_e value of each propagation step. Figure 7 shows the axial position vs time trajectories of the test-electron set, with $\gamma_{\ell,0} = 1.05 - 10^3$ ($\varepsilon_e = 0.5 - 511$ MeV) in variable steps. The dotted trajectory lines correspond to the case where radiation friction was neglected by omitting $\mathbf{F}_{\text{RR}}^Q$ from the numerical integration of Eq. (4). From this calculation, it is seen that for the laser parameters under consideration, the effect of RR is negligible for $\gamma_{\ell,0} \lesssim 10$. For increasingly larger values of $\gamma_{\ell,0}$, if radiation recoil is not accounted for, it is predicted that an electron will traverse the laser field largely unperturbed (dotted lines). By contrast, RR causes all of the lepton trajectories to reverse with minimal delay (solid lines), once the initial axial momentum is depleted by photon emission.

E. Parameter scans

We have performed QED-PIC calculations in 2D in which the laser and seed- γ beam properties were varied over a wide range. The per-species energy conversion efficiencies are plotted in Fig. 8 as functions of the field amplitude and incident γ energy/density. The star data point is the common parameter case, and is the two-dimensional version of the calculation discussed in Sec. II A. In Fig. 8(a), it is apparent that a critical a_0 value exists (in this case, $a_0 \approx 250$), below which secondary γ

radiation is negligible. This is because the electric field and the vector potential must be sufficiently strong in order to, respectively, generate $e^\pm$ pairs and effect their radiative trapping.

From Fig. 8(b), the γ energy conversion efficiency scales rather weakly with the seed energy, increasing from 1.1% (when $\varepsilon_{\gamma,i} = 51$ MeV) to 2.5% (255 MeV). By contrast, Fig. 8(c) shows that increasing the seed γ density is the most reliable way to increase the γ energy conversion efficiency, which rises from 2.5% (when $n_{\gamma,i} = n_0$) to 11.8% ($n_{\gamma,i} = 5n_0$).

III. CONCLUSION

A laser- γ -beam collision can give rise to a unique condition in which an electron-positron pair plasma is generated and subsequently confined to the laser field. Typically, a charged particle is repelled by nonlinear forces away from the high-field regions, but if the radiation-reaction force is sufficiently strong, then it is possible to establish an equilibrium of forces that breaks this behavior. This situation is desirable because as the leptons copropagate with the intense field, they continue to radiate strongly, up-converting laser photons into γ -rays.

Using the quantum electrodynamics-extended particle-in-cell method, we have demonstrated this effect and analyzed dependencies of the process, such as its scaling with field amplitude and seed γ energy and density. To observe this effect experimentally, it is important to utilize parameters such that the pair-production efficiency is maximized ($\chi_\gamma \sim 1$), but also that the field is sufficiently strong for lepton radiation reaction to play a role ($\chi_e \sim 1$). Thus, it entails a balance between the nonlinear Breit-Wheeler and Compton scattering processes.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

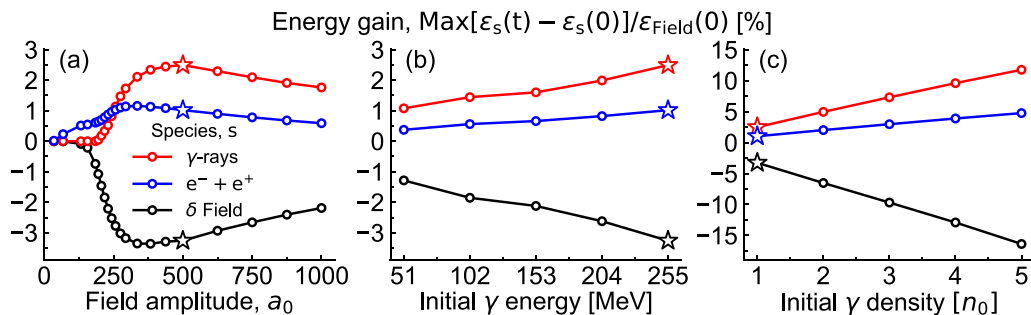


FIG. 8. Maximum energy conversion efficiency of each species, normalized to the initial laser field energy. Parameter scans over (a) input field amplitude, (b) initial γ energy, and (c) initial γ density. Star point: common parameter case.

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