Brilliant GeV gamma-ray flash from inverse Compton scattering in the QED regime

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Abstract
An all-optical scheme is proposed for studying laser plasma based incoherent photon emission from inverse Compton scattering in the quantum electrodynamic regime. A theoretical model is presented to explain the coupling effects among radiation reaction trapping, the self-generated magnetic field and the spiral attractor in phase space, which guarantees the transfer of energy and angular momentum from electromagnetic fields to particles. Taking advantage of a prospective $\sim 10^{23} \text{ W cm}^{-2}$ laser facility, 3D particle-in-cell simulations show a gamma-ray flash with unprecedented multi-petawatt power and brightness of $1.7 \times 10^{23} \text{ photons s}^{-1} \text{ mm}^{-2} \text{ mrad}^{-2}/0.1\%$ bandwidth (at 1 GeV). These results bode well for new research directions in particle physics and laboratory astrophysics exploring laser plasma interactions.

Keywords: laser plasma interaction, gamma-ray emission, quantum electrodynamics effect, radiation reaction effect, electron angular momentum dynamics

(Some figures may appear in colour only in the online journal)

1. Introduction

Gamma-rays are ubiquitous in our daily life, having applications in areas such as container security initiatives [1], gamma-knife surgery [2], nuclear medical imaging [3] and food storage [4]. While in the vastness of the Universe, photons with energies ranging from several MeV to tens of TeV [5–7] result from various different processes, such as energetic cosmic rays [8, 9], luminous pulsars [10] and gamma-ray bursts [11, 12]. Data from gamma-ray bursts were first published in results from Vela satellites [13] which were then quickly verified by data from Soviet satellites [14]. The ability of cosmic sources to emit such intense gamma-rays indicates that investigating this extreme environment is a promising route to discover new physical phenomena which are impossible in earth-bound laboratories.

An alternative method of generating violent emissions of gamma-rays is through the interaction of petawatt (PW, $10^{15}$ W) lasers and plasmas in the laboratory. Several multi-PW laser facilities, such as the Extreme Light Infrastructure (ELI) [15] and Exawatt Center for Extreme Light Studies (XCELS) [16], are expected to operate at intensities beyond $10^{23} \text{ W cm}^{-2}$ in the next few years. Under $\sim 10^{23} \text{ W cm}^{-2}$, various theoretical schemes have been put forward for multi-MeV photon sources with tens of percent for the total conversion efficiency. These include reinjected electron synchrotron radiation [17], skin-depth emission [18], radiation reaction facilitating gamma-rays [19] and sandwich target design [20]. Nevertheless, none of them has the ability to extend the energy of a gamma-ray photon up to several GeV, which is highly desirable for exploring laboratory astrophysics [21, 22]. Recently, exploiting the interplay between pair cascades [23] and anomalous radiative trapping [24], an ultrabright GeV photon source can be achieved in laser dipole waves [25]. However, the scheme of dipole wave fields

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Figure 1. Scheme of the ultra-brilliant GeV gamma-ray source with helical structure. (a) and (b) show light being reflected before and after electron passing through the target, respectively.

(24, 26, 27) requires multiple beams focused into a tiny point symmetrically, which is still an experimental challenge nowadays. Here we report on an alternative all-optical scheme to realize brilliant GeV gamma-ray emission via irradiating only one multi-PW circularly polarized (CP) pulse on a compound target in the quantum electrodynamic (QED) regime. This all-optical backscatter scheme is already available in experiments for relatively lower intensity circumstances [28–32].

2. Theoretical model for the coupling effect

In the realm of nonlinear QED, electrons are able to emit a huge amount of kinetic energy in the form of high-energy photons \( \gamma_{\text{ph}} \), as a result of absorbing a certain number \( n \) of laser photons \( \gamma_n \), \( e^+ + n\gamma_n \rightarrow e^- + \gamma_{\text{ph}} \). The invariant parameters \( \eta = (e\hbar/m_e^2c^3)\gamma_{\text{ph}}\gamma_{\text{ph}}' = E_{RF}/E_{\text{Sch}} \) and \( \chi = (e\hbar^2/2m_e^2c^4)\gamma_{\text{ph}}\gamma_{\text{ph}}' \) characterize the discrete photon emission process, where \( e \) is the electron charge, \( m_e \) the electron rest mass, \( h \) the Planck constant, \( c \) the velocity of light in vacuum, \( F_{\mu\nu} \) the field tensor and \( p'(k') \) the electron’s (photon’s) four-momentum. \( E_{RF} \) denotes the electric field in the electron’s rest frame and \( E_{\text{Sch}} = m_e^2c^3/\hbar\approx 1.3 \times 10^{18} \text{ V m}^{-1} \) is the characteristic field of the Schwinger limit [33]. When \( \eta \leq 1 \): (1) The radiation process should be described by probabilistic quantum emission rather than viewed as continuous. (2) The corresponding quantum weakening correction for radiation is inevitable [34, 35]. When an electron beam co-propagates with the laser pulse, the electric force offset by the magnetic field effect results in \( \eta \approx 0 \), which is undesirable for high-energy photon emission [22, 35]. However, if the laser counter-propagates with the electron beam, it leads to an enhancement as \( \eta \approx 2\gamma E_L/E_{\text{Sch}} \), where \( \gamma \) is the relativistic Lorentz factor of the electron and \( E_L \) is the polarized laser field. This colliding configuration can not only lower the threshold for QED cascade from seed electrons [36], but also facilitate the generation of a gamma-ray explosion [37, 38] and pair plasma [23, 39–41].

To exploit the counter-propagating configuration, in this paper, a CP femtosecond pulse was irradiated on a compound target (see figure 1) consisting of a near-critical-density (NCD) plasma slab and a solid foil. Here the solid foil plays the role of a plasma mirror [28–32], spontaneously reflecting the driven light and triggering the subsequent Compton backscattering. Generally, when a CP pulse of \( 10^{19}–10^{23} \text{ W cm}^{-2} \) propagates in the NCD target, the ionized electrons can be transversely expelled from the central area to form a plasma channel [42, 43]. An injected electron can experience a direct laser acceleration process, and a collimated energetic electron bunch can be produced when its oscillation frequency in the channel field is close to the light frequency witnessed by the electron [44–46]. However, under the higher intensity of \( \sim 10^{23} \text{ W cm}^{-2} \), the injected electrons are mostly expelled from the central region and a hollow channel is merely filled with laser radiation [47]. More interestingly, a large number of electrons will be trapped back into the channel if radiation reaction (RR) is taken into account [47, 48], where transverse ponderomotive force is properly balanced by the radiation recoil.

It should be noted that the interaction between the laser and the NCD plasma is very complicated, where the filamentation instability [49], hosing instability [50] or non-optimal laser plasma matching [51] can destroy the laser propagation and the channel’s shape. Here, a relatively large spot radius and a low plasma density are adopted to avoid these detrimental influences and guarantee a stable channel. To understand the underlying mechanism behind the impact of RR on this scheme, the single electron model is utilized to depict the interaction between the laser transverse field \( E_L \) and self-generated fields in the plasma channel. Based on previous work [43, 45, 52], self-generated fields in the channel include a radial electrostatic field \( E_{Sr} = k_S r\hat{r_e} \), a longitudinal electric field \( E_{S3} \) and a quasistatic azimuthal magnetic field \( B_{S0} = -k_B r\hat{r_\theta} \), where \( k_S \) and \( k_B \) can be seen as constant and are related to the plasma density. The time derivative of the
ponderomotive phase \( \psi \) can be written as
\[
\frac{d\psi}{dt} = \omega_J - \omega_L = \frac{e}{\gamma m_e} (v_j \langle k_B \rangle + \langle k_E \rangle)
\]
\[
- (1 - v_j / v_{ph}) \omega_0.
\]
(1)

Here \( \omega_J \) = \( e(v_j k_B + k_E) / (\gamma m_e) \) is the electron betatron frequency and \( v_j \) (\( v_e \)) is the electron longitudinal (transverse) velocity. \( \omega_L = (1 - v_j / v_{ph}) \omega_0 \) is the Doppler-shifted laser frequency witnessed by the electron, where \( \omega_0 \) is the laser frequency and \( v_{ph} = c / \sqrt{1 - \omega_0^2 / (\gamma^2 \omega_L^2)} \) is the laser phase velocity [53]. \( v_j \) is the plasma frequency. \( \psi \) is the relative phase between the electron rotation and the periodic laser field. The time derivative of the electron Lorentz factor is expressed as
\[
\frac{d\gamma}{dr} = -eE \cdot \mathbf{v} - \mathbf{f}_{rad} \cdot \mathbf{v} = -e(v_j \mathbf{E}_L \cos \psi + v_j (\mathbf{E}_j)) / m_e c^2
\]
\[
- \omega_{rad} \omega_0 \beta a_s^2 \gamma^2 G(\gamma).
\]
(2)

Here \( E_L \) is the light electric field amplitude. Since the stochasticity of photon emission is difficult to simplify into a precise formula, the discontinuous influence is neglected in the single model and the quantum-corrected RR force \( \mathbf{f}_{rad} \approx -G(\eta) e_{rad} m_e c_0 \beta a_s^2 \gamma^2 \) is used in equation (2) to qualitatively analyze the RR influences, where \( G(\eta) \approx (1 + 12 \eta + 31 \eta^2 + 3.7 \eta^3)^{-4/3} \) is the quantum weakening factor [34]. The effects arising from the discrete stochasticity in RR are beyond the scope of this manuscript, and these are worth discussing in future work. \( \omega_{rad} = 4 \pi e \omega_0 / 3 \lambda_0 \) is a dimensionless ratio, where \( e_0 = e^2 / m_e c^2 \approx 2.8 \times 10^{-15} \) m is the classical electron radius and \( \lambda_0 \) is the laser wavelength. \( \beta = \mathbf{v} / c \) is the normalized electron velocity and \( a_s = eE_{Sch} / m_e c \omega_0 \) is the normalized Schr"{o}dinger field. The parameters in the above equations are time dependent and are probably in an especially complicated form, so that the average values denoted by \( \langle \rangle \) are used. From equations (1)–(2), it can be found that the phase space \((\psi, \gamma)\) has a fixed point [54, 55] at \((\psi_0, \gamma_0) = (\cos^{-1} - r_{rad} \omega_0 \beta a_s^2 \gamma^2 G(\gamma) m_e c_0 - e_0, 0) / \mathbf{v}_j \mathbf{E}_j \). To determine the system’s dynamic properties from equations (1)–(2) in \((\psi, \gamma)\) space, the perturbation expansion near \((\psi_0, \gamma_0)\) of equations (1)–(2) was made, and quadratic terms were dropped to approach the characteristic Jacobian matrix \( \mathbf{J}_{\mathbf{a}} \) [54, 55]:
\[
\mathbf{J}_{\mathbf{a}} \approx \begin{pmatrix}
0 & -1 / 2 \sqrt{\gamma m_e} (v_j \langle k_B \rangle + \langle k_E \rangle) \\
\gamma v_j \mathbf{E}_L \sin \psi - e_{rad} m_e c^2 \omega_0 \beta a_s^2 \gamma^2 G(\gamma) / \gamma & (\mathbf{v}_j \mathbf{E}_j) / \gamma v_j \end{pmatrix}.
\]
(3)

Without the RR effect, the trace and determinant of the Jacobian matrix are \( \text{tr}(\mathbf{J}_{\mathbf{a}}) = 0 \) and \( \text{det}(\mathbf{J}_{\mathbf{a}}) > 0 \) when the right lower RR term is canceled, which shows that \((\psi_0, \gamma_0)\) is a center without any source or sink property [54, 55]. In contrast, with the RR effect included, at fixed point \( \text{tr}(\mathbf{J}_{\mathbf{a}}) < 0 \) and \( \text{det}(\mathbf{J}_{\mathbf{a}}) > 0 \) indicating that its behavior converts from center to spiral sink attractor [24, 56–58]. The emergence of the sink attractor illustrates that a large fraction of the radiation-trapped electrons tend to possess the same relative phase \( \psi_0 \) with respect to the laser electric field and the helical density structure is an intrinsic rotary manner of the electric field of the CP laser. Due to electrons moving in the same direction as the pulse, the electric field \( E_L \) counteracts the force from the laser magnetic field \( B_L \) leading to \( \eta \approx \gamma (E_L + \mathbf{v} \times B_L) / E_{Sch} \approx 0 \) and \( \text{tr}(\mathbf{J}_{\mathbf{a}}) \approx 0 \). Notwithstanding, the strong self-generated magnetic field \( B_{sd} \approx n_e B / (2 \varepsilon_0 c) \) (here \( \varepsilon_0 \) is the permittivity of a vacuum, \( n_e \) is the RR-trapped electron density and \( R \) is the channel radius) approaching the order of the driven laser field [20] gives \( \eta \approx -2 \varepsilon_{rad} \beta^2 e^2 B_{sd}^2 / m_e \omega_0^2 < 0 \) and enables the attractor effect on achieving such a helical electron bunch (HEB). The nearby electrons are attracted to possess the identical Lorentz factor \( \gamma_0 = e(v_j \langle k_B \rangle + \langle k_E \rangle) / m_e (1 - v_j / v_{ph}) \omega_0^2 \). The total angular momentum (AM) along the longitudinal x axis, i.e. \( L = \gamma p_x - c \gamma p_y \), acquired by the HEB can also be estimated as
\[
L \approx - \int \mathbf{e}_{\mathbf{r}} \mathbf{E}_L \mathbf{c} \mathbf{E}_L \mathbf{E}_j dt \quad i = 1, 2, 3...
\]
where \( r_\pm \) is the electron transverse radius and the index \( i \) refers to the \( i \)th electron. From equation (4) we can see that the laser could transfer its spin angular momentum (SAM) to the HEB only when most of the electrons possess the same ponderomotive phase \( \psi_0 \), otherwise the ensemble average leads to \( \sum_i \gamma \sim \psi_i \approx 0 \). Therefore, coupling effects among RR trapping, the self-generated magnetic field and the spiral attractor in phase space all enhance the net AM gain and realize the HEB. Eventually, discrete photon emission [59–61] is triggered through the inverse Compton scattering (ICS) between the HEB and reflected light, where prolific high-energy photons inheriting a large fraction of the electrons’ energy and AM are generated.

3. Particle-in-cell (PIC) simulation results

The feasibility and robustness of this scheme are demonstrated using the self-consistent 3D PIC code EPOCH [62]. A Monte Carlo probabilistic model [63, 64], which is based on QED-corrected synchrotron cross sections, has been successfully implemented and coupled with the subsequent reduction of the electron momentum. Each particle is assigned an optical depth \( \tau \) at which it emits according to \( P = 1 - e^{-\tau} \), where \( P \in [0,1] \) is chosen at random to consider the quantum correction in the emission processes as well as the straggling. The rates of photon production, \( d\tau / dt = (\sqrt{3} \alpha_E c) / (\lambda_c \gamma) \int_0^{\gamma / 2} dx F(\eta, \chi) / \chi \), are then solved until the optical depth is reached, when the emission event occurs [63]. Here, \( \alpha_E \) is the fine structure constant, \( \lambda_c = \hbar / (m_e c) \approx 3.9 \times 10^{-12} \) m is the Compton wavelength and \( F(\eta, \chi) \) is the quantum synchrotron spectrum [63].

The incident \( 1.2 \times 10^{23} \) W cm\(^{-2}\) CP pulse propagates along the X direction with a profile of \( a = a_0 e^{-(u-v^2) / 2 \nu^2} e^{-x^2 / 2 \nu^2} \sin(\omega_0 t) \), where \( \tau_0 = 5T_0 \) denotes the
intensity with a full width at half maximum (FWHM) of 25.6 fs ($T_0 \approx 3.3$ fs is the laser period) and $a_0 = eE_L / \omega_0 c$, is the spot size ($\lambda_0 = 1.0 \ \mu$m). The simulation box is $80\lambda_0 \times 40\lambda_0 \times 40\lambda_0$ in the $X \times Y \times Z$ directions respectively, and has been uniformly divided into $3200 \times 800 \times 800$ cells. A hydrogen slab with initial density $n_e = 2n_c$, is located between $10\lambda_0$ and $60\lambda_0$, and aluminium foil of $n_a = 700n_c$ is placed from $60\lambda_0$ to $80\lambda_0$, where $n_c = m_0\omega_0^2/4\pi e^2$ is the critical density [65]. The hydrogen slab and aluminium foil contain four and 16 macroparticles per cell (for both species), respectively. For reference, there is no obvious difference in our results when we double the number of macroparticles per cell.

The electron density distributions in $\gamma - \psi$ space at $t = 50T_0$, for the cases with and without RR are presented in figures 2(a) and (b). The Lorentz factor at the fixed point, obtained from equations (1)-(2) as $\gamma_0 \approx \frac{c\nu(H_k) + \nu(H_{0})}{m_e(t - \nu/H_{0}^2)^2}$, where $\nu(H) \approx \frac{n_a}{2n_c}$, $\omega_0 \approx \frac{\sqrt{\omega_0^2}}{\omega_0 c}$, and $\nu_{ph} \approx \frac{\omega_0}{\sqrt{1 - n_e/(\omega_0 c)}}$ are taken into account and $\nu(H)$ is neglected, as the transverse static electric field is relatively weak compared with the self-generated magnetic field. Substituting $n_e = 2n_c$, $a_0 = 300$ and $|\nu| = 0.9863c$ (from simulation parameters and results) into the above equation leads to $\gamma_0 \approx 3416$. Considering $\nu_{rad} = 1.18 \times 10^{-8} \nu^2$, $\beta \approx 1$, and $a_s \approx 4.1 \times 10^5$, $\eta \approx \frac{R_{He}}{a_s} \approx 0.165$, $G(\eta) \approx 1$, $\langle E \rangle_0 \approx 0.015 E_L$, and $v_L = 0.165c$, the relative phase is deduced to be $\psi_0 = \arccos\left(\frac{c\nu(H_k) + \nu(H_{0})}{m_e(t - \nu/H_{0}^2)^2}\right)$, which is in good agreement with our theoretical prediction of equation (4). The RR force switches on, most of the electrons possess a relative phase of $\psi = 2.3$ in figure 2(b), which is in good agreement with our theoretical predictions. Since neither RR trapping nor attractor emerging occurs, the number density of electrons in figure 2(a) is relatively small compared to the RR case and it does not behave like the attractor modulated distribution. The self-generated azimuthal magnetic field $B_{\phi}$ averaged over the channel cross plane $z = 0$ is plotted in figure 2(c) with maximum $\approx 0.6$ MT (normalized value is $60m_e\omega_0 / e \approx 0.2B_L$, where $B_L$ is the laser magnetic amplitude) at $t = 65T_0$, which demonstrates that RR recoil enhances the $B_{\phi}$ generation due to the larger trapped electron current along the longitudinal axis. This kind of self-generated magnetic field in the channel can not only enhance gamma photon emission [20], but also help accelerate ions in the rear surface of the target [66], which has already been verified in experiments under lower laser intensity with a shock-compressed gas target [67]. The temporal evolution of electron numbers inside the plasma channel, and their total AM $L = \sum_{i} n_i P_i - z_i P_i$, are recorded in figure 2(d) for both cases. It is found that RR not only boosts the electron accumulation inside the channel but also facilitates the AM transfer to the HEB, which is in good agreement with the theoretical prediction of equation (4). The RR force prevents electrons from being expelled transversely, resulting in an increase of electrons, from 172 nanocoulombs.
(nC) to 291 nC at \( t = 65T_0 \). The enhancement of electron current strengthens the \( B_s \theta \), which gives a positive feedback on spiral attractor merging in phase space, and effectively favors AM transformation from the laser’s SAM to the HEB’s AM.

The electron density distributions for the cases with and without RR are shown in figures 3(a)−(b). Here the emergence of a helical spatial structure depends on the RR impact, which accords with the attractor facilitating electron density modulation with a frequency similar to that of the laser electric field in equation (3). When RR is switched off, a ball of electrons is injected into the tail of the plasma channel and can be accelerated by the longitudinal electric field \( E_x \). The distributions of \( E_x \) are plotted in figure 3(c)−(d) for the cases with and without RR. Since the quantity of electrons in the channel for the RR case is much higher than that for no RR, the shield effect weakens the accelerating field more in the RR case than it does when there is no RR.

Since the ponderomotive force of the CP pulse avoids the longitudinal oscillation at twice the optical frequency [65], plasma in the second layer cannot be heated violently and the driven light is substantially reflected. Under the colliding configuration, the parameter \( \eta \approx 2\gamma E_L/E_{Sch} \gtrsim 1 \) indicates that the discrete incoherent photon emission [35] gives a more appropriate description than does the coherent electromagnetic wave radiation derived from the Liénard–Wiechert retarded potential [68]. A volume snapshot of the photon energy density at \( t = 70T_0 \) is shown in figure 4(a) where the photon beam inherits a helical spatial structure and the transverse size of the source is about 1.5 μm. The gamma-ray flash duration is \( \sim 16 \) fs, roughly equal to half the laser pulse duration because the driven pulse and trapped electrons completely overlap inside the channel. The angular-spectral distribution calculated by accumulating the forward photons at \( t = 70T_0 \) over the entire simulation region is shown in figure 4(b)−(c). Most of the energetic photons are highly collimated and are predominantly located within an emission polar angle \( \phi \approx 15^\circ \) \( \phi \approx 30^\circ \) for energies higher than 1 GeV (100 MeV). In a 0.1% bandwidth (BW) around 1 GeV we have \( 1.05 \times 10^8 \) photons, implying a brightness of \( 1.7 \times 10^{25} \) photons s\(^{-1}\) mm\(^{-2}\) mrad\(^{-2}\)/0.1%BW for the GeV gamma-ray emission. The corresponding source brilliances at 100 MeV and 10 MeV are \( 2.3 \times 10^{24} \) and \( 1.5 \times 10^{25} \) photons s\(^{-1}\) mm\(^{-2}\) mrad\(^{-2}\)/0.1%BW, respectively. A comparison between different photon sources is illustrated in figure 5. Our ICS scheme predominantly aims for high
brilliance at around 1 GeV. Another dipole wave field can achieve the brightest gamma photon emission, with $9 \times 10^{24}$ photons $s^{-1}$ mm$^{-2}$ mrad$^{-2}$/0.1%BW at 1 GeV [25], but the dipole wave needs to be realized through symmetrically colliding multi-pulses, which is still a challenge experimentally. Here our scheme of shooting one laser pulse onto a double layer target is the most efficient method to generate brilliant GeV gamma-ray sources [17–20] and it is more experimentally accessible.

4. Discussion and conclusion

Figure 6(a) shows the exponential decay spectrum of photons covering a higher energy range from 1 MeV to several GeV, with a cutoff energy at 2.9 GeV, along with the spectra for electrons before the ICS process ($t = 60T_0$) and after ($t = 70T_0$). The nonlinear QED regime predicts that most photons are emitted with an energy $\hbar \nu_{\text{gh}} \approx 0.44/\tau m_e c^2$ [23, 34] which carries a large fraction of the electron’s kinetic energy. It is obvious that the number of high-energy electrons is drastically curtailed with the cutoff-energy declining from 3.9 GeV to 2.5 GeV, and simultaneously most of energy is converted into gamma photons. The temporal evolutions of the particle energy are illustrated in figure 6(b), where 14.5%, 4.2% and 0.108% of the total laser energy is transferred into gamma-ray photons with energies above 1 MeV, 100 MeV and 1 GeV respectively. For energies above 100 MeV and 1 GeV, the photons are emitted almost exclusively by the ICS process during $65T_0 < t < 70T_0$. Based on the power radiated by a single electron, $P_{\text{rad}} = (4\pi \alpha e^2 / 3\lambda_c) \alpha c n^2 G(\eta)$ [63, 64], the instantaneous radiation power of this regime can be estimated as

$$P_{\text{rad}} \approx \begin{cases} N_e \frac{4\pi \alpha e^2 c^2}{3\lambda_c} \left( \frac{\gamma B_{\text{ref}}}{E_{\text{Sch}}} \right)^2 G \left( \frac{\gamma B_{\text{ref}}}{E_{\text{Sch}}} \right) & \text{if } t < t_{\text{ref}}, \\ N_e \frac{4\pi \alpha e^2 c^2}{3\lambda_c} \left( \frac{2\gamma E_t}{E_{\text{Sch}}} \right)^2 G \left( \frac{2\gamma E_t}{E_{\text{Sch}}} \right) & \text{if } t \geq t_{\text{ref}}. \end{cases}$$

Here, $N_e$ is the electron number, $t_{\text{ref}} = 65T_0$ is the time of the light reflecting and $\eta$ is approximated by $\gamma B_{\text{ref}} / E_{\text{Sch}}$ at $t < t_{\text{ref}}$ and $2\gamma E_t / E_{\text{Sch}}$ at $t \geq t_{\text{ref}}$ respectively. The length of NCD plasma $l = 50 \mu$m is not comparable with the laser depletion length $L_{\text{depletion}} \approx c_0 t_0 n_e / n_e = 750 \mu$m [43, 69], and as a result a large part of the laser energy is reflected and back-scattered with the electron bunch. In addition, when the laser propagates in the NCD plasma, both its intensity and spot size will change due to self-focusing, self-modulation, etc. The radius of the self-generated channel is determined by the balance between the ponderomotive force and charge separation fields. Here, we choose a laser spot almost the same as the radius of such channel, which results in no significant change in the laser transverse size during propagation in near critical plasma. Then we assume they are constant in the estimation of equation (5). Equation (5) predicts the radiation power $P_{\text{rad}} \approx 0.63$ PW ($t < t_{\text{ref}}$) and $P_{\text{rad}} \approx 19.2$ PW ($t \geq t_{\text{ref}}$), which qualitatively agrees with the simulation results in figure 6(b), implying the nonlinear QED
ICS-based gamma-ray source power is of the same order as the infrared incident laser.

The transfer of axial AM from the laser to the particles is plotted in figure 6(c). The oscillation of electron and proton AM is due to the interplay of charged particles with the laser electromagnetic field. The different sign of electric charge causes the opposite oscillation direction in electrons and protons. Since the spiral attractor results in a fixed relative phase between the electron velocity and the laser electric field, the overall AM of the electrons rises gradually before ICS. However, photons do not interact with the laser field and their AM has a moderate growth before ICS. The photons are predominantly emitted from electrons modulated by the spiral attractor during $65T_0 < t < 70T_0$ so that a sharp photon AM increase, and a pronounced electron AM drop, occur in the ICS process. In terms of quantum mechanics, the AM carried by a photon of the CP laser is $\sigma = \pm 1$ for spin motion. The total AM absorbed from the laser is approximately expressed as $L_1 = \frac{\delta W}{\hbar a_0} = 1.70 \times 10^{-12} \, \text{kg m}^2 \text{s}^{-1}$, where $W_1$ is the whole laser energy and $\delta$ is the absorbing ratio. During the ICS process, AM is more efficiently transferred from electrons to gamma-rays and eventually the AM of photons reaches $8.2 \times 10^{-14} \, \text{kg m}^2 \text{s}^{-1}$, 4.8% of the total laser SAM. In addition, a parameter scan has been carried out to investigate energy conversion efficiency for a wide range of densities, $0.2 - 20n_c$, of first layer plasma with thickness 50 $\mu$m (see figure 6(d)). It was found that there is an optimal condition $n_0 \sim n_c$ for realizing the twisted GeV gamma-ray emission. The disadvantage for relatively rarefied plasma ($n_e = 0.2n_c$) is its lack in number of trapped helical electrons, so that insufficient electron quantity accounts for deficient gamma-ray production, while for relatively dense circumstances ($n_e \gtrsim 10n_c$) the driven laser tends to deplete most of their energy in the first slab, without any remnants to trigger the ICS process.

In conclusion, we have shown how an ultra-intense and ultra-bright GeV gamma-ray flash can be achieved by irradiating a prospective $1.2 \times 10^{23}$ W cm$^{-2}$ laser on a compound plasma target in the nonlinear QED regime. The initial energetic HEB results from the coupling effects among RR trapping, the self-generated magnetic field and the emergence of a spiral attractor in $\gamma - \psi$ space. The helical gamma-ray flash inherits considerable AM and energy from the parent electron beam through Compton backscattering between the HEB and the reflected driven pulse. The final photon source—with unprecedented power of 20 PW and brightness of $1.7 \times 10^{23}$ photons s$^{-1}$ mm$^{-2}$ mrad$^{-2}$/0.1%BW (at 1 GeV)—might enable significant development of applications in particles physics and laboratory astrophysics. Our scheme is also feasible in the laboratory system where cluster jets [70] or nanotube foams [71] can be utilized for NCD plasma generation and a solid foil acts as a plasma mirror to reflect a laser. Such parameters for gamma-ray sources will be...
accomplished with the next generation of multi-PW laser facilities in the future.

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References

[1] Lun Y V, Wong C W, Lai K-H and Cheng T 2008 Transport Rev. 28 21
[2] Ganz I 2012 Gamma Knife Surgery (New York: Springer)
[3] Eisen Y, Shor A and Mardor I 1999 Nucl. Instrum. Methods Phys. Res. A 428 158
[4] Lado B H and Yousef E A 2002 Microbes Infect. 4 433
[5] Lamb R and Macomb D 1997 Astrophys. J. 488 872
[6] Abdou A et al 2010 Astrophys. J. Lett. 710 L92
[7] Aharonian F et al 2004 Astrophys. J. 614 897
[8] Kulsrud R and Pearce W P 1969 Astrophys. J. 156 445
[9] Hunter S D et al 1997 Astrophys. J. 481 205
[10] Romani R W 1996 Astrophys. J. 470 469
[11] Piran T 2005 Rev. Mod. Phys. 76 1143
[12] Mészáros P 2002 Annu. Rev. Astron. Astrophys. 40 137
[13] Klesbades R W, Strong I B and Olson R A 1973 Astrophys. J. 182 L85
[14] Mazets E, Golentsevskii S and Il’inskii V 1974 JETP Lett. 19 77
[15] Extreme Light Infrastructure project, http://www.eli-laser.eu.
[16] Exawatt Center for Extreme Light Studies, http://www.xecls.iauras.ru.
[17] Brady C S, Ridgers C, Arber T, Bell A and Kirk J 2012 Phys. Rev. Lett. 109 245006
[18] Ridgers C, Brady C S, Duclos R, Kirk J, Bennett K, Arber T, Robinson A and Bell A 2012 Phys. Rev. Lett. 108 165006
[19] Nakamura T, Koga J K, Esirkepov T Z, Kando M, Korn G and Bulanov S V 2012 Phys. Rev. Lett. 108 195001
[20] Stark D, Toncian T and Arefiev A 2016 Phys. Rev. Lett. 116 185003
[21] Remington B A, Drake R P and Ryutov D D 2006 Rev. Mod. Phys. 78 755
[22] Bulanov S, Esirkepov T Z, Kando M, Koga J, Kondo K and Korn G 2015 Plasma Phys. Rep. 41 1
[23] Bell A and Kirk J G 2008 Phys. Rev. Lett. 101 200403
[24] Gonoskov A, Bashinov A, Gonoskov I, Harvey C, Ilberton A, Kim A, Marklund M, Mourou G and Sergeev A 2014 Phys. Rev. Lett. 113 014801
[25] Gonoskov A, Bashinov A, Bastrakov S, Efimenko E, Ilberton A, Kim A, Marklund M, Meyerov I, Muraviev A and Sergeev A 2017 Phys. Rev. X 7 041003
[26] Gonoskov I, Aiello A, Heugel S and Leuchs G 2012 Phys. Rev. A 86 053836
[27] Gonoskov A, Gonoskov I, Harvey C, Ilberton A, Kim A, Marklund M, Mourou G and Sergeev A 2013 Phys. Rev. Lett. 111 060404
[28] Phuoc K T, Corde S, Thaury C, Malka V, Tafzi A, Goddet J-P, Shah R, Sebhan S and Rousse A 2012 Nat. Photon. 6 308
[29] Chen S et al 2013 Phys. Rev. Lett. 110 155003
[30] Powers N D, Ghebregziabher I, Golovin G, Liu C, Chen S, Banerjee S, Zhang J and Umstadter D P 2014 Nat. Photon. 8 28
[31] Sarri G et al 2014 Phys. Rev. Lett. 113 224801
[32] Khrennikov K, Wenz J, Buck A, Xu J, Heigoldt M, Veisz L and Karsch S 2015 Phys. Rev. Lett. 114 195003
[33] Schwinger J 1951 Phys. Rev. 82 564
[34] Kirk J G, Bell A and Arka I 2009 Plasma Phys. Control. Fusion 51 085008
[35] Di Piazza A, Müller C, Hatsagortsyan K and Keitel C 2012 Rev. Mod. Phys. 84 1177
[36] Grismayer T, Vranic M, Martins J L, Fonseca R A and Silva L O 2016 Phys. Plasmas 23 056706
[37] Nerush E, Kostyukov I Y, Fedotov A, Narozhny N, Elkins N and Ruhl H 2011 Phys. Rev. Lett. 106 035001
[38] Gong Z, Hu R H, Shou Y R, Qiao B, Chen C E, He X T, Bulanov S S, Esirkepov T Z, Bulanov S V and Yan X Q 2017 Phys. Rev. E 95 013210
[39] Zhu X-L, Yu T-P, Sheng Z-M, Yin Y, Turcu I C E and Pukhov A 2016 Nat. Commun. 7 13686
[40] Jurka M, Klimo O, Bulanov S, Esirkepov T Z, Gelfer E, Bulanov S, Weber S and Korn G 2016 Phys. Rev. E 93 023207
[41] Chang H, Qiao B, Xu Z, Xu X, Zhou C, Yan X, Wu S, Borghesi M, Zepf M and He X 2015 Phys. Rev. E 92 053107
[42] Pukhov A, Sheng Z-M and Meyer-ter Vehn J 1999 Phys. Plasmas 6 2847
[43] Pukhov A 2002 Rep. Prog. Phys. 66 47
[44] Liu B, Wang H, Liu J, Fu L, Xu Y, Yan X and He X 2013 Phys. Rev. Lett. 110 055002.
[45] Hu R, Liu B, Lu H, Zhou M, Lin C, Sheng Z, Chen C-E, He X and Yan X 2015 Sci. Rep. 5 15499
[46] Arefiev A V, Breizman B N, Schollmeier M and Khudik V N 2012 Phys. Rev. Lett. 108 1145004
[47] Ji L, Pukhov A, Kostyukov I Y, Shen B and Akli K 2014 Phys. Rev. Lett. 112 145003
[48] Chang H, Qiao B, Huang T, Xu Z, Zhou C, Gu Y, Yan X, Zepf M and He X 2017 Sci. Rep. 7 45031
[49] Honda M, Meyer-ter Vehn J and Pukhov A 2000 Phys. Rev. Lett. 85 2128
[50] Huang T, Zhou C, Zhang H, Wu S, Qiao B, He X and Ruan S 2017 Phys. Rev. E 95 043207
[51] Mourou G, Chang Z, Maikischak A, Nees J, Bulanov S, Bychenkov V Y, Esirkepov T Z, Naumova N, Pegoraro F and Ruhl H 2002 Plasma Phys. Rep. 28 12
[52] Liu B, Hu R, Wang H, Wu D, Liu J, Chen C, Meyer-ter Vehn J, Yan X and He X 2015 Phys. Plasmas 22 080704
[53] Decker C and Mori W 1995 Phys. Rev. E 51 1364
[54] Jordan D and Smith P 2007 Nonlinear Ordinary Differential Equations: an Introduction for Scientists and Engineers (Oxford: Oxford University Press on Demand)
[55] Hirsch M W, Smale S and Devaney R L 2012 *Differential Equations, Dynamical Systems, and an Introduction to Chaos* (New York: Academic)

[56] Esirkepov T Z, Bulanov S S, Koga J K, Kando M, Kondo K, Rosanov N N, Korn G and Bulanov S V 2015 *Phys. Lett. A* 379 2044

[57] Gong Z, Hu R, Shou Y, Qiao B, Chen C, Xu F, He X and Yan X 2016 *Matter Radiat. Extremes* 1 308

[58] Kirk J 2016 *Plasma Phys. Control. Fusion* 58 085005

[59] Ritus V 1985 *J. Russ. Laser Res.* 6 497

[60] Neitz N and Piazza A Di 2013 *Phys. Rev. Lett.* 111 054802

[61] Blackburn T, Ridgers C, Kirk J G and Bell A 2014 *Phys. Rev. Lett.* 112 015001

[62] Arber T et al 2015 *Plasma Phys. Control. Fusion* 57 113001

[63] Duclos R, Kirk J G and Bell A 2010 *Plasma Phys. Control. Fusion* 53 015009

[64] Ridgers C, Kirk J G, Duclos R, Blackburn T, Brady C, Bennett K, Arber T and Bell A 2014 *J. Comput. Phys.* 260 273

[65] Gibbon P 2004 *Short Pulse Laser Interactions with Matter* (Singapore: World Scientific)

[66] Bulanov S, Esarey E, Schroeder C, Leemans W, Bulanov S, Margarone D, Korn G and Haberer T 2015 *Phys. Rev. Spec. Top. Accel. Beams* 18 061302

[67] Helle M, Gordon D, Kaganovich D, Chen Y, Palastro J and Ting A 2016 *Phys. Rev. Lett.* 117 165001

[68] Jackson J D 1999 *Classical Electrodynamics* (New York: Wiley)

[69] Lu W, Tzoufras M, Joshi C, Tsung F, Mori W, Vieira J, Fonseca R and Silva L 2007 *Phys. Rev. Spec. Top. Accel. Beams* 10 061301

[70] Fukuda Y et al 2009 *Phys. Rev. Lett.* 103 165002

[71] Ma W et al 2007 *Nano Lett.* 7 2307