Deciphering \textit{in situ} electron dynamics of ultrarelativistic plasma via polarization pattern of emitted $\gamma$-photons

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Understanding and interpretation of the dynamics of ultrarelativistic plasma is a challenge, which calls for the development of methods for \textit{in situ} probing the plasma dynamical characteristics. We put forward a new method, harnessing polarization properties of $\gamma$-photons emitted from a non-pre-polarized plasma irradiated by a circularly polarized pulse. We show that the angular pattern of $\gamma$-photon linear polarization is explicitly correlated with the dynamics of the radiating electrons, which provides information on the laser-plasma interaction regime. Furthermore, with the $\gamma$- photons circular polarization originating from the electron radiative spin-flips, the plasma susceptibility to quantum electrodynamical processes is gauged. Our study demonstrates that the polarization signal of emitted $\gamma$-photons can be a versatile information source, which would be beneficial for the research fields of laser-driven plasma, accelerator science, and laboratory astrophysics.

Ultrarelativistic plasma produced at cutting-edge laser facilities with intensities already reaching the level of $10^{23}$ W/cm$^2$ \cite{1,3}, is favorable for investigation of new regimes of electron and ion acceleration \cite{4,6}, and hard photon emissions \cite{7,13}, to explore astrophysical phenomena in a laboratory \cite{14,16}, and to probe nonlinear QED processes in ultrastrong fields \cite{17,24}. The description of plasma in such extreme conditions is a challenge even for numerical particle-in-cell (PIC) simulations, which calls for the development of new methods for \textit{in situ} probing the plasma dynamical characteristics and verification of the employed plasma models. Unlike underdense plasma being noninvasively diagnosed through optical probes or charged particle radiography \cite{22,24}, the fast evolving ($\sim$fs) ultrarelativistic plasma, associated with sufficiently strong fields \cite{25}, radiative particle trapping \cite{26,28}, or $e^+e^-$ pair cascades \cite{29,31}, tends to be energetic and overdense, which hinders the use of conventional diagnostic techniques. New approaches based on XFEL beams \cite{32} or ejected spin-polarized electrons \cite{33} were recently proposed to measure Megatester-level magnetic fields within overdense plasma. Nevertheless, interrogating and verifying the \textit{in situ} transient electron dynamics remains a challenging covet.

Recently, the successful decoding of field properties nearby a black hole \cite{34} re-stimulated interest in diagnostics based on photon polarization \cite{35}. While polarized light is vulnerable to magneto-optic disturbance \cite{36}, a high-frequency $\gamma$-photon is robust during penetration of the plasma depth \cite{37}. In contrast to the routinely detected quantities of arrival time and energy, the $\gamma$-photon polarization (GPP), provides new insights into the relativistic jet geometry \cite{38} and magnetic field configuration \cite{39}, which allows to identify cosmic neutrino scattering \cite{40}, dark matter annihilation \cite{41}, and acceleration mechanisms surrounding crab pulsars \cite{42}. Prompted by the role of GPP in astrophysical scenarios, the question arises on its possible use to diagnose the \textit{in situ} electron dynamics in ultrarelativistic plasma.

This Letter aims to find the distinct relationship between the spatial features of the GPP and the time-resolved motion of plasma electrons, and in this way deduce the dynamical properties of plasma and the regime of interaction. Using 3D PIC simulations, we study the polarization-resolved $\gamma$-photon emission in an ultrarelativistic plasma driven by a circularly polarized pulse [see Fig. 1(a)]. The collective orientation of the $\gamma$-photons’ linear polarization (LP) resembles a spiral shape with the rotation tendency determined by the acceleration status of the radiating electrons. To quantifies the degree of rotation tendency, we introduce the polarization angle $\delta\phi$, as the deviation of the orientation of GPP with respect to the azimuthal direction. It is determined by the electrons’ transient acceleration gradient, and its angle dependence can serve as a classifier to distinguish laser-plasma interaction regimes with different electron dynamics, such as with the electrons’ single- or multi-cycle resonance oscillations, or the longitudinal braking emission. Furthermore, the $\gamma$-photons’ circular polarization (CP), originating from the accumulated longitudinal polarization of plasma electrons due to the quantum radiative spin-flips, is shown to provide a measure of the susceptibility of the ultrarelativistic plasma to QED processes.

When an electron interacts with an electromagnetic wave $\mathbf{A} = a_0 e^{i\xi} \hat{\mathbf{e}}_y + e_0 a e^{i(\xi - \pi/2)} \hat{\mathbf{e}}_z$ with the normalized amplitude $a_0$, ellipticity $e = 1$, and phase $\xi = \omega_0 t - k_0 x$ ($\omega_0/k_0 = \nu_{ph}$), the electron motion is described by $p_y z = A_{y,z} m_e c^2$, $y, z \sim -i A_{y,z}/(\Gamma k_0)$, with the dephasing $\Gamma \equiv \gamma_e -(p_z/m_e c \nu_{ph})$. The laser fields predominantly govern the electron dynamics, while the self-generated azimuthal magnetic field $\mathbf{B}_\phi = \epsilon_k (-y \hat{\mathbf{e}}_z + z \hat{\mathbf{e}}_y)$ \cite{43} acts as a perturbation. The radically quasi-static electric field is neglected due to the ion motion compensating the charge separation \cite{44}. The polarized $\gamma$-photon emission and electron radiative spin-flips is determined by the strong-field quantum parameter $\chi_{\nu, ph} \equiv (\epsilon_0 \hbar/m_e c^4) |F_{\mu\nu} p^\nu|$ with the field tensor $F_{\mu\nu}$ and the momentum $p^\nu$ of the elec-
The time evolution of the electron energy spectrum as a function of time can be quantified by \( \delta \phi \), the relative angle between the \( \gamma \)-photon azimuthal direction and the electron momentum direction perpendicular to the electron momentum, \( \mathbf{a}_\perp \equiv \mathbf{a} - (\mathbf{a} \cdot \mathbf{\hat{v}}) \mathbf{\hat{v}} \), where the hat symbol denotes the unit vector. Thus, the polarization orientation can be derived

\[
\begin{align*}
\hat{a}_{\perp,y} &\approx -\sin \phi \left( \frac{\Gamma}{\gamma_e} + \frac{\kappa_e \cos \theta}{\epsilon \Gamma} \right) - \frac{(\beta \cdot \mathbf{E}) \cos \phi}{\gamma_e}, \\
\hat{a}_{\perp,z} &\approx \cos \phi \left( \frac{\Gamma}{\gamma_e} + \epsilon \kappa_e \cos \theta \right) - \frac{(\beta \cdot \mathbf{E}) \sin \phi}{\gamma_e},
\end{align*}
\]

where \( \beta = \mathbf{v}/c \), \( \theta = \arctan[(p_y^2 + p_z^2)^{1/2}/p_x] \) and \( \phi = \arctan(2p_z/p_y) \). When the electron energy gain is negligible, i.e. \( -\beta \cdot \mathbf{E} = 0 \), the orientation of the \( \gamma \)-photon LP would be along the azimuthal direction \( \mathbf{a}_\perp = (\mathbf{\perp} \cdot \mathbf{\hat{v}}) \mathbf{\hat{v}} \), which collectively resembles multiple concentric rings with each polarization segment along the azimuthal direction [Fig. 1(b)]. The deviation of the \( \gamma \)-photon LP orientation from the azimuthal direction can be quantified by \( \delta \phi \in [-90^\circ, 90^\circ] \), which is the relative angle between \( \hat{a}_\perp \) and \( \mathbf{a}_\perp \) [44] and is calculated as

\[
\delta \phi \approx \arcsin \left\{ \frac{\mathbf{\perp} \cdot \mathbf{E}}{\sqrt{\left( \Gamma + (\gamma_e \kappa_e \cos \theta / \Gamma) \right)^2 + (\beta \cdot \mathbf{E})^2}} \right\}.
\]

If the radiating electron is undergoing acceleration with \( -\beta \cdot \mathbf{E} > 0 \) (\( -\beta \cdot \mathbf{E} < 0 \)), the GPP orientation \( \delta \phi > 0 \) (\( \delta \phi < 0 \)) corresponds to the counter-clockwise (clockwise) spiral tendency in the angular distribution of \( \gamma \)-photon LP as shown in Fig. 1(c) [Fig. 1(d)].

To examine the GPP features, we performed 3D PIC simulations, where a non-pre-polarized slab is illuminated by a circularly polarized pulse (\( \epsilon = 1 \)). The laser intensity \( I_0 \approx 1.7 \times 10^{23} \text{W}/\text{cm}^2 \) is equivalent to \( a_0 \approx 350 \) for the wavelength \( \lambda_0 = 1 \text{ \mu m} \). The pulse has a duration \( \tau_0 = 25 \text{ fs} \) and focal spot size 2.6 \( \mu \text{m} \) (FWHM intensity measure). The plasma slab has a thickness \( d_0 = 10 \text{ \mu m} \) and consists of electrons and carbon ions with the density \( n_e = 30n_i \) and \( n_i = 5n_e \), respectively, \( n_e \) is the plasma critical density. The influences of radiative spin-flips, spin-dependent photon emission, and photon polarization effects have been incorporated in the EPOCH code [45, 46].

Inside the interacting plasma, the electrons tend to form a helical density structure [47], undergo betatron oscillation [48], and radiate multi-MeV photons [49]. The orientation of the emitted \( \gamma \)-photon LP exhibits a counter-clockwise spiral tendency at \( t = 10 \text{ fs} \) [Fig. 1(e)], reproducing well the analytical prediction for the accelerating electron. Here, the averaged polarization angle is \( \delta \phi \approx 30.6^\circ \) and the LP degree \( \rho_{LP} \approx 15.3\% \). The clockwise spiral tendency in Fig. 1(f) implies the deceleration of plasma electrons occurring later at \( t = 40 \text{ fs} \). The time-resolved \( \delta \phi \) explicitly reflects the electrons being predominantly accelerated (decelerated) at \( t \lesssim t_{e^+} \) (\( t \gtrsim t_{e^-} \)) [see Fig. 1(g)], where \( t_{e^\pm} \approx 35 \text{ fs} \) is the electron energy saturation time. Consequently, the moment of \( \delta \phi \)
changing sign, defined as the reversal time $t^R_{\theta}$, should be equal to $t^R_{E}$, which is confirmed by simulations for different parameters [45]. Although the measurement of $t^R_{\theta}$ can provide time-resolved plasma information, the timing accuracy of $\sim 10$ fs is not available yet for the current $\gamma$-photon polarimetry [50]. Therefore, we turn to the investigation of the angle-dependence of $\delta \phi (\theta)$ of all emitted $\gamma$-photons during the interaction [Fig. 2].

Three distinct typical angle distributions of $\delta \phi (\theta)$ are possible when varying $a_0$ and $n_e$ [Fig. 2(a)]. Each typical distribution corresponds to a specific category of the electron dynamics: the single-cycle resonance oscillation (SRO) regime [$a_0=350$; $n_e=2n_c$], the multi-cycle resonance oscillation (MRO) regime [$a_0=350$; $n_e=30n_c$], and the longitudinal braking emission (LBE) regime at weak fields and high density [$a_0=150$; $n_e=30n_c$].

**Single-cycle resonance oscillation** (at strong fields and low densities) – the typical electron experiences an angle-dependent acceleration and deceleration procedure after being injected into one laser period [Fig. 2(a)]. This injection is triggered by the suppressed dephasing $\Gamma \approx \int (1 - \beta_x) E_x \, dt$ due to a negative $E_x$ exerted on the electron. Here, the oscillating laser field $E_x \sim (\lambda_0/2\pi) \delta E_x/\delta r \approx 10^{14}$ V/m rather than the quasi-static self-generated field is the dominant term of the whole longitudinal electric field. When the electron moves in a range with negative $E_x$ at $6 < t < 12$ fs, its dephasing value decreases from $\Gamma/\gamma_e \approx 1.4$ to 0.2. If the relative angle between the laser vector potential and electron’s transverse momentum is defined as $\Psi := \angle -\beta \cdot \mathbf{E}$, the electron dynamics can be described by $d\gamma_e/\gamma_e = -\beta_0 \sin \phi \sin \Psi - \beta_x E_x - \beta \cdot \mathbf{f}_{RR}$ and $d\Psi/\gamma_e = (1 - v_x/v_{ph}) - \omega_\beta$ in $(\Psi, \gamma_e)$ space, where $\mathbf{f}_{RR}$ is the radiation reaction force and $\omega_\beta \approx \sqrt{|v_x| \kappa_0 \gamma_e}/c$. The time evolution of the Lorentz factor $\gamma_e$ [Fig. 2(a)] manifests that the interacting scenario takes place merely in one laser period at $20 < t < 60$ fs, which is further confirmed by the electron evolution in the space of $(\Psi, \gamma_e)$ [Fig. 2(b)]. As illustrated in Fig. 2(c), features of $\delta \phi (\theta > 35^\circ) < 0$, $\delta \phi (10^\circ < \theta < 35^\circ) > 0$, and $\delta \phi (\theta < 10^\circ) < 0$ correspond to the electron’s injection termination, phase matching acceleration, and dephasing deceleration, respectively. The panel (b) in Fig. 2 indicates that the electron dynamics in the plasma channel is quasi-synchronous during a single resonance oscillation, leading to strong coherence of the emitted $\gamma$-photons. Thus, the LP degree of the SRO regime $P_{LP} = 40.7\%$ is approximately one order of magnitude higher than those of the MRO (3.2%) and LBE (5.3%) regimes [see Fig. 2(b)].

**Multi-cycle resonance oscillation** (at strong fields and high densities) – as the gradient of plasma magnetic field $\kappa_0 \approx (m_e \omega_0^2/|e|c(n_e/n_c))$ [10] is enhanced due to the raised density, the increased oscillation frequency $\omega_\beta \approx n_e^{1/2}$ readily mismatches with the relatively laser frequency $\delta \omega/\gamma_e$. Consequently, the electron, associated with the abrupt change of $\theta$ by the imposed field $E_x$, repeatedly experiences dephasing and slides into the next accelerating phase [see Fig. 2(a)], which is further verified by its multiple rotation in $(\Psi, \gamma_e)$ space [Fig. 2(b)]. Although the MRO scenario can be qualitatively decomposed into multiple single-cycle resonance oscillations, the multiple injections with varying locations and fast dephasing deteriorate the synchronous motion [Fig. 2(a)], which gives rise to a diffusive distribution of electron evolution in $(\Psi, \gamma_e)$ phase space [Fig. 2(b)] and a low LP degree $P_{LP} \approx 3.2\%$ of emitted $\gamma$-photons. As shown in Fig. 2(c), the dependence of photon number distribution $N_{ph}$ on angle $\theta$ and acceleration status $-v \cdot \mathbf{E}$...
FIG. 4. The electron dynamics of the MRO regime. (a) The same as Fig. 3(a) but for the MRO regime, where the dashed blue line denotes the normalized field $E_x = |e| E_x/m_e c \omega_0$. (b) The single electron trajectory (circles) and evolution tendency of a bunch of electrons (small dots) in $(\Psi, \gamma_c)$ space, where the rainbow color refers to time. (c) The dependence of the $\gamma$-photon number distribution $N_{\phi\gamma}$ on $-\mathbf{v} \cdot \mathbf{E}$ and $\theta$, where the dashed line shows $N_{\phi\gamma}(-\mathbf{v} \cdot \mathbf{E})$ and the dotted line displays the symmetry of $N_{\phi\gamma}(-\mathbf{v} \cdot \mathbf{E} < 0)$ at $-\mathbf{v} \cdot \mathbf{E} > 0$ for comparison.

FIG. 5. The electron dynamics of the LBE regime. (a) The representative electron trajectory in $(x, y)$ plane, where the yellow circles denote the emitted $\gamma$-photons with energy $\varepsilon_{\gamma ph} > 10 m_e c^2$. (b) The time evolution of the photon emission power $d\varepsilon_{\gamma ph}/dt$.

demonstrates that overall the acceleration is dominant in the electron’s energy exchange with the laser field, which agrees with the distribution of $\delta \phi(\theta < 40^\circ) > 0$.

**Longitudinal braking emission** (at relatively weak fields and high densities) — If a strong charge separation sustained at the interface between the laser wave front and the plasma channel edge, the electron channeling into the plasma is hampered. The electron is primarily braked and emits $\gamma$-photons within a collimated polar angle $\theta$, while being exposed to the positive longitudinal electric field $E_x$ [Fig. 3(a)(b)]. In the braking emission stage, the term of $-v_y E_\parallel (-v_y E_x)$ contributes 86% (14%) of the whole $-\mathbf{v} \cdot \mathbf{E}$, and the averaged orientation of GPP is $\delta \phi \approx -8.9^\circ$. Therefore, the $\delta \phi(\theta) < 0$ holds over a large range of $\theta < 40^\circ$. The braking dynamics develops as follows. The positive $E_x$ moves forward with a velocity $v_m \sim 0.32c$, where the new replenished electrons with a near-light velocity $v_x \gtrsim 0.75c$ quickly catch up with the moving $E_x$ and then get braked there. The polarization pattern in the $(\theta, \phi)$ space for the LBE regime is distinct [cf. Fig. S6 in [45] with Fig. 3(c)] determined by the main cycle of the laser pulse and is CEP dependent.

In Fig. 6 we present the range of the different regimes in the parameter space of $a_0$ and $n_e$, which can be identified by the $\gamma$-photon polarization. The criterion of separation of the SRO and MRO regimes is estimated from the following condition that the electron undergoes one period of resonant oscillation during the interaction: $\omega_p/(l_0/c) \sim 2 \pi$, which is reformulated as $n_e \sim (\pi m_e c^2/e^2) a_0 l_0^{-2}$.

The threshold of LBE is estimated as follows. The LBE stems from the intense quasistatic longitudinal electric field, which is sustained when the laser pulse is readily depleted within the plasma slab: $(v_{ph} - v_y) a_0/v_{ph} \gtrsim 70c$, where $v_{ph} \sim c/\sqrt{1 - n_e/(a_0 n_e)}$ and $v_y = c^2/v_{ph}$. The latter conditions give the threshold density for LBE: $n_e \gtrsim n_e^* \sim (m_e c \omega_0/2e^2) a_0 l_0^{-1}$.

Besides the LP, $\gamma$-photons are partially circularly polarized (CP), see [45], which originates from the spin polarization of plasma electrons, caused by electron radiative spin flips. The latter are governed by the QED quantum strong-field parameter $\chi_c$. Thus, the CP of emitted $\gamma$-photons can be a characteristic of the QED properties of the laser-driven plasma. We provide analytical estimation of the CP degree in [45] and show its agreement with PIC simulation results.

Concluding, we demonstrate that the polarization properties of $\gamma$-photons emitted from an ultrarelativistic plasma driven by a circularly polarized pulse provide exclusive information on the in situ electron dynamics, which allows to identify three specific regimes of laser-plasma interaction, as well as the plasma QED status. Our diagnostic scheme via the emitted $\gamma$-photon polar-
ization is mainly applied in the laser-driven ultrarelativistic overdense plasma, which cannot be measured by the conventional optical probes. In addition, since the ultrarelativistic plasma is generally associated with sufficiently strong fields, the requirement of the ion energy on the proton radiography is unfeasible either. Therefore, the advantage of the diagnostic based on $\gamma$-photon polarization is its applicability in the energetic and overdense plasma. Note that the requirement of the angular resolution ($\sim 1^\circ$) of GPP is satisfied by the gamma-ray polarimetry parameters envisaged in Ref. [51], and thus the method presented here is likely to be experimentally feasible in the near future. This diagnostic tool may appear beneficial for better understanding of phenomena in broad high-intensity interaction scenarios including ion acceleration [52] [55], direct laser acceleration [48], high-harmonic generation [56, 57], brilliant photon emission [58] [59], ultradense nanopinches [60], and $e^- e^+$ pair plasma cascades [61].

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