

All-Optical Generation of Dense, Multi-GeV, Longitudinally-Polarized Positron Beams

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(Dated: October 1, 2025)

The production of high-yield, longitudinally polarized positron beams represents an outstanding challenge in advanced accelerator science. Laser-driven schemes offer a compact alternative but typically yield only transverse polarization, or require pre-polarized electron beams, and struggle to efficiently accelerate positrons to high energies. Here, we introduce an all-optical scheme that overcomes these limitations by integrating positron generation, acceleration, and spin manipulation in a unified framework. Through a head-on collision between an ultraintense, circularly polarized laser pulse and a counterpropagating unpolarized electron beam, we drive a robust QED cascade. The nonlinear Breit-Wheeler process within the cascade produces positrons that are born directly within the strong laser field. Crucially, these positrons are instantaneously captured and accelerated to multi-GeV energies (up to ~ 9 GeV) via a direct laser acceleration mechanism, while their spins are simultaneously rotated to longitudinal alignment by the field dynamics. Our Monte-Carlo simulations confirm the simultaneous achievement of a high positron yield ($\sim 20 e^+/e^-$), a high average longitudinal polarization ($\sim 50\%$), and GeV-scale energies. This all-optical source, feasible at upcoming ultraintense laser facilities, presents a compact and efficient solution for applications in collider physics and fundamental high-energy experiments.

Longitudinally spin-polarized positrons, with spin aligned parallel to momentum, are indispensable for probing fundamental symmetries and testing the Standard Model in high-energy physics. Their helicity sensitivity enables precision studies of electroweak couplings at future colliders such as the International Linear Collider (ILC) [1, 2], investigations of chiral dynamics in QED cascades [3], and searches for CP-violating physics beyond the Standard Model [4]. These endeavors demand high-flux positron sources delivering GeV beams with high longitudinal polarization ($> 30\%$) and substantial yields ($> 1.5 e^+/e^-$) [4, 5].

Conventional positron polarization techniques, however, are constrained by a fundamental trade-off among yield, polarization degree and efficiency. Radioactive β^+ sources produce beams of low intensity and high divergence [6]. Synchrotron-based methods, such as the Sokolov-Ternov effect, require hour-long polarization buildup times [7]. The most advanced approach, helicity transfer from circularly polarized γ rays via Bethe-Heitler pair production in solid targets, is fundamentally limited by depolarization from multiple Coulomb scattering [8]. This results in theoretical yields below $0.01 e^+/e^-$ [9] and experimental yields as low as $\sim 10^{-5} e^+/e^-$ [10, 11],

primarily due to limitations in the photon spectrum and yield-polarization trade-offs during collimation.

Laser-driven all-optical schemes have emerged as promising alternatives, leveraging ultraintense fields to generate positrons via the nonlinear Breit-Wheeler (NBW) process in asymmetric laser setups [12–14]. While these methods enhance yield and efficiency, they typically produce only transversely polarized positrons with limited charge ($\lesssim 1 e^+/e^-$). Proposals employing solid targets with 100-PW-class lasers [15, 16] or ultradense electron beams [17] could achieve nanocoloumb-level yields but still fail to produce the essential longitudinal polarization required for applications [4, 5, 18, 19]. Polarization rotators [20–22] offer a potential solution but introduce significant complexities, including large footprints and substantial particle losses from energy-bandwidth mismatch.

An alternative helicity-transfer scheme [23] could directly yield longitudinal polarization but requires pre-polarized GeV electron beams, a capability yet to be demonstrated experimentally in all-optical setups [24, 25]. Furthermore, accelerating positrons to GeV energies in plasma wakefields remains challenging due to their inherent defocusing in electron-driven wakes [26], unlike

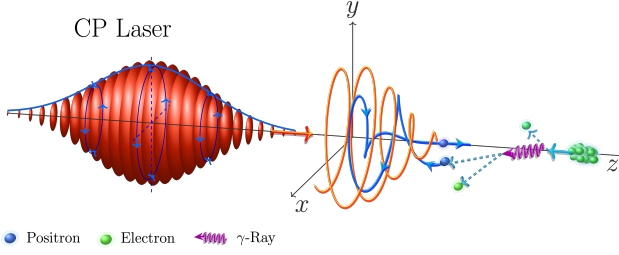


FIG. 1. Generation of longitudinally polarized positrons via collision of a counterpropagating ultraintense laser pulse and unpolarized electron beam. NBW pair production generates e^+e^- pairs from γ -photons created by NCS. Newborn positrons, initially propagating along $-z$, are reflected and backward-accelerated by the laser field. During their spiral trajectory, spin precession induced by the phase-mismatched field efficiently converts transverse polarization into longitudinal polarization.

electrons which are efficiently accelerated [27, 28]. Consequently, the generation of dense, multi-GeV, longitudinally polarized positron beams from unpolarized electrons remains an outstanding challenge for all-optical approaches.

In this Letter, we present a compact, all-optical scheme that simultaneously generates, accelerates, and polarizes positrons in a single stage. We demonstrate that a head-on collision between a circularly polarized, ultraintense laser pulse and a counterpropagating, unpolarized electron beam directly yields longitudinally polarized positrons with high yield ($\sim 20 e^+/e^-$), GeV-scale energies (up to ~ 9 GeV), and substantial polarization ($\sim 50\%$ on average, peaking above 70%). The mechanism initiates with nonlinear Compton scattering (NCS), producing abundant high-energy photons, followed by NBW pair creation, which imparts an initial transverse polarization to the e^+e^- pairs. Crucially, the positrons are born within the strong-field vacuum of the laser pulse. Radiation reaction rapidly damps their transverse momentum, facilitating reflection and trapping by the laser field. Subsequent direct laser acceleration (DLA) [29–31] via the $\mathbf{v} \times \mathbf{B}$ force sustains multi-GeV energy gain. Simultaneously, the phase-mismatched field conditions induce rapid spin precession, quantitatively converting the initial transverse polarization into a longitudinal alignment. This intrinsic integration of all key functionalities—without requiring pre-polarized beams, external converters, or complex beamlines—establishes a practical pathway toward compact polarized positron sources for next-generation high-energy physics.

A Monte Carlo method [23, 32] that self-consistently incorporates polarization effects in strong-field QED is employed to simulate the polarization dynamics of photons, electrons, and positrons throughout the interaction. This approach leverages the local constant field

approximation (LCFA) [25, 33–37], whose validity is well-established for ultraintense laser fields characterized by $a_0 \equiv |e|E_0/(m\omega_0) \gg 1$ [34, 35]. Within the LCFA framework, the probability of photon emission (and subsequent pair production) is governed by the quantum strong-field parameter $\chi_{e,\gamma} \equiv |e|\sqrt{-(F_{\mu\nu}p^\nu)^2}/m^3$ [35]. Here, E_0 and ω_0 denote the amplitude and frequency of the laser field, respectively; e and m are the electron charge and mass; $F_{\mu\nu}$ is the electromagnetic field tensor; and p^ν is the four-momentum of the electron (or photon for pair production). Relativistic units ($c = \hbar = 1$) are used throughout this work.

A representative result for polarized positron generation is presented in Fig. 2. The simulation involves a counter-propagation setup between an ultra-intense, tightly focused, circularly polarized Gaussian laser pulse and an ultra-relativistic electron beam. The laser pulse is characterized by the following parameters: a peak intensity of $I_0 \approx 2.76 \times 10^{24}$ W/cm² (corresponding to $a_0 = 1000\sqrt{2}$), a wavelength $\lambda_0 = 1 \mu\text{m}$, a focal radius $w_0 = 5\lambda_0$, and a pulse duration $\tau = 5T_0$, where T_0 is the optical period. The incident electron beam is configured with parameters typical of a laser-wakefield-accelerated source [28, 38, 39]. It is initially unpolarized, with a mean spin polarization vector $(\bar{S}_x, \bar{S}_y, \bar{S}_z) = (0, 0, 0)$, a mean energy $\varepsilon_0 = 6$ GeV, a relative energy spread $\Delta\varepsilon_0/\varepsilon_0 = 6\%$, and an angular divergence $\Delta\theta = 0.2$ mrad. The bunch contains $N_e = 1 \times 10^6$ electrons, distributed uniformly over a longitudinal length $L_e = 6\lambda_0$, and possesses a transverse Gaussian profile with waist $w_e = 2\lambda_0$ and standard deviations $\sigma_x = \sigma_y = 0.6\lambda_0$. We emphasize that substantial polarized positron yields are also achievable at lower, more accessible laser intensities, as shown in Fig. 5(a) and the Supplemental Material [40]. The experimental feasibility is supported by current laser technology capable of reaching intensities above 10^{23} W/cm² [41], with 100-PW-class facilities underway [42]. Moreover, laser wakefield acceleration can now deliver multi-GeV electron beams [38, 39].

Figures 2(a)–(c) present the angular distributions of the reflected positron number density, along with their average longitudinal polarization $\bar{S}_\parallel$ and mean energy $\bar{\varepsilon}_+$. Positrons are predominantly distributed within the polar angle range $\theta \in [0, 30^\circ]$, with a total yield of 2.58×10^7 (equivalent to $25.8 e^+/e^-$), an average polarization of 46.8% , and a mean energy of 2.45 GeV. A pronounced annular region between $\theta = 5^\circ$ and 12° exhibits enhanced values of both $\bar{S}_\parallel$ and $\bar{\varepsilon}_+$ [purple curves in Figs. 2(b) and (c)], reaching 48.9% and 2.56 GeV on average, respectively. Given the relatively low particle density at smaller angles, including the central region has only a minor effect on overall polarization. Therefore, for practical experimental applications, it is beneficial to collect positrons within a broader angular range. For instance, selecting positrons within $\theta \in [0, 12^\circ]$ results in a beam with 48.0% polarization, a total yield of $19.4 e^+/e^-$, and

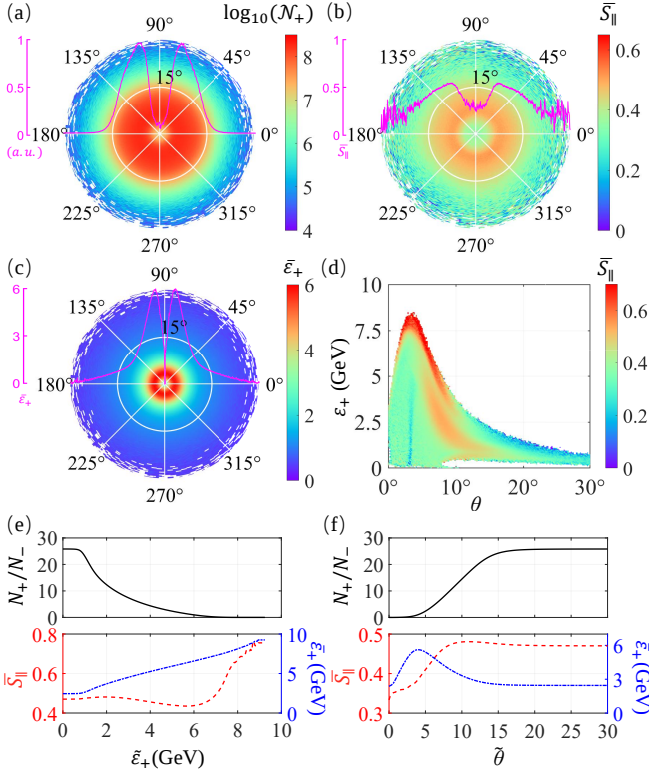


FIG. 2. (a) Angular distribution of number density $\log_{10}(\mathcal{N}_+)$, with $\mathcal{N}_+ = dN_+/(\sin\theta d\theta d\phi)$, (b) average longitudinal polarization $\bar{S}_{\parallel}$ and (c) average energy $\bar{\varepsilon}_+$ of positrons vs $\theta \in [0, 30^\circ]$ and $\phi \in [0, 360^\circ]$. Here, θ and ϕ are the polar and azimuthal angles with respect to $+z$ axis. Purple curves are normalized density, $\bar{S}_{\parallel}$ and $\bar{\varepsilon}_+$ with respect to θ along $\phi = 0, 180^\circ$. (d) Distribution of $\bar{S}_{\parallel}$ vs ε_+ and θ . (e) Positron yield (black solid), average polarization (red dashed), and average energy (blue dash-dotted) as functions of the lower energy cutoff $\tilde{\varepsilon}_+$; (f) the same quantities as functions of the angular acceptance $\tilde{\theta}$. The energy selection corresponds to collecting positrons with energies from $\tilde{\varepsilon}_+$ to 10 GeV, while the angular selection corresponds to collecting positrons within a polar angle from 0° to $\tilde{\theta}$.

a mean energy of 2.87 GeV.

For clarity, Fig. 2(d) illustrates the average longitudinal polarization $\bar{S}_{\parallel}$ as a function of both energy ε_+ and angle θ . Positron energies extend up to 9 GeV, with $\bar{S}_{\parallel}$ increasing markedly at higher energies—reaching up to 72.7%, at $\theta \approx 3^\circ$. The dependence of $\bar{S}_{\parallel}$ on both θ and ε_+ enables the extraction of highly longitudinally polarized positron beams through post-selection in energy and angle, as shown in Figs. 2(e) and (f). For example, selecting positrons with energies above 7.6 GeV yields $\bar{S}_{\parallel} = 60.2\%$ and a normalized yield of $0.022 e^+/e^-$, while those above 7.0 GeV achieve $\bar{S}_{\parallel} = 51.2\%$ with a yield of $0.118 e^+/e^-$. Similarly, selecting positrons within a collection angle of $\tilde{\theta} = 10^\circ$ yields $\bar{S}_{\parallel} = 48.0\%$, a normalized yield of 14.5

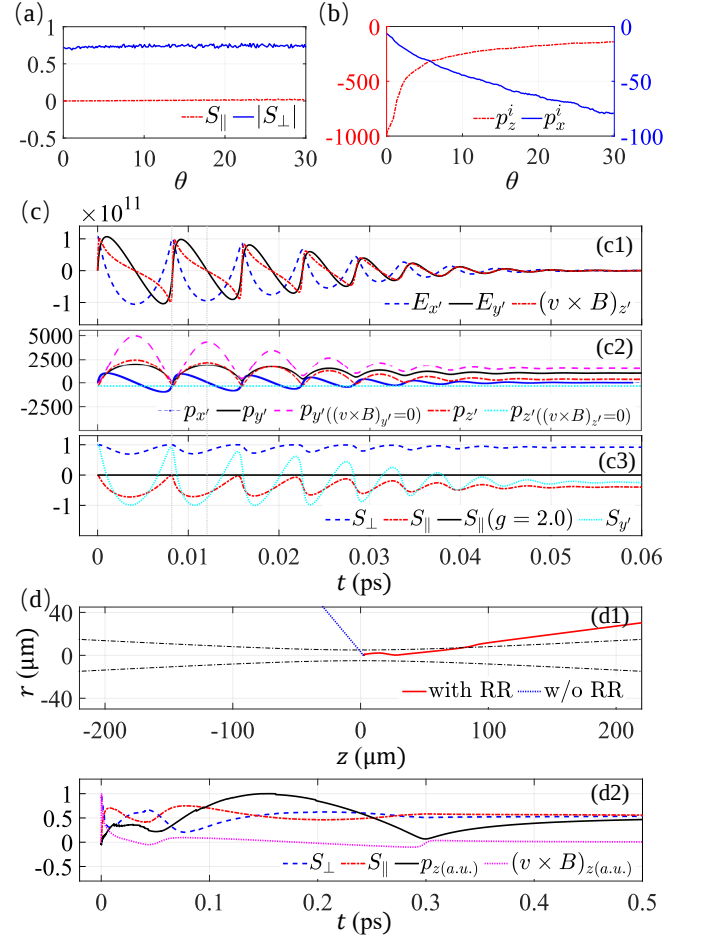


FIG. 3. (a) Initial longitudinal $S_{\parallel}^i$ and transverse $|S_{\perp}^i|$ polarization of a positron at birth versus θ at $\phi = 0^\circ$. (b) Corresponding initial momentum components p_z^i , p_x^i (in units of mc). (c) Temporal evolution for a representative positron (radiation reaction neglected) in a plane-wave laser field: (c1) laser field components $E_{x'}$, $E_{y'}$, and the longitudinal Lorentz force component of $(\mathbf{v} \times \mathbf{B})_{z'}$; (c2) momentum components $p_{x'}$, $p_{y'}$, $p_{z'}$; (c3) polarization components $S_{\perp}$, $S_{\parallel}$ (for physical and $g = 2$ g -factor), and $S_{y'}$. (d) Spatial and dynamic evolution in the realistic laser field: (d1) spatial trace $r = \sqrt{x^2 + y^2}$ with the laser focus profile (black dash-dotted lines); (d2) dynamics of $|S_{\perp}|$, $S_{\parallel}$, p_z and $(\mathbf{v} \times \mathbf{B})_z$.

e^+/e^- and a mean energy of 3.30 GeV, whereas a broader angle of $\tilde{\theta} = 15^\circ$ results in $\bar{S}_{\parallel} = 47.5\%$ with a yield of $24.3 e^+/e^-$ and a mean energy of 2.54 GeV.

The underlying mechanisms of positron polarization and acceleration are elucidated in Figs. 3 and 4. Parent photons exhibit a centrosymmetric radial polarization distribution, corresponding to a vanishing average polarization vector $\bar{\xi} = (0, 0, 0)$ for the full beam (see Supplemental Material [40]), consistent with previous reports [43]. Consequently, newly created positrons display negligible initial longitudinal polarization ($\bar{S}_{\parallel}^i = 1.2\%$)

but substantial transverse polarization ($|\bar{S}_\perp^i| = 73\%$ [40]) [Fig. 3(a)]. These positrons are born with minimal transverse momenta and propagate primarily forward [Fig. 3(b)].

To unravel the governing dynamics, we simulate the trajectory and polarization evolution of a representative position in a plane-wave laser field with Gaussian temporal profile, neglecting radiation reaction (RR) [Fig. 3(c)]. The positron is initialized near the laser peak at phase η' with energy 190 MeV (the mean energy for all the positrons at birth) and a polarization vector aligned with the instantaneous quantum spin axis [23, 40]—parallel to the electric field [$\mathbf{S} = (0, 1, 0)$]. Born within the laser field, the positron experiences an asymmetric field structure in the y' -direction [Fig. 3(c1)], acquiring a pronounced drift velocity of $p_{y'}$ [black solid curve, Fig. 3(c2)]. This leads to strong acceleration via the $\mathbf{v} \times \mathbf{B}$ mechanism [red dash-dotted curve, Fig. 3(c1)] along the laser propagation direction [red dash-dotted curve, Fig. 3(c2)], yielding significant final momentum of p_z . Throughout the interaction, spin precession dominates the polarization evolution: $S_\parallel$ rises from 0 to 0.396 while $S_\perp$ declines from 1 to 0.918, confirming efficient transverse-to-longitudinal polarization transfer [Fig. 3(c3)].

This conversion is described by the spin evolution equation [44]:

$$\frac{dS_\parallel}{dt} = -\frac{e}{m} S_\perp \cdot \left[\left(\frac{g}{2} - 1 \right) \mathbf{v} \times \mathbf{B} + \left(\frac{gv}{2} - \frac{1}{v} \right) \mathbf{E} \right], \quad (1)$$

where g is the energy-dependent gyromagnetic factor. For $g(\chi_e) = 2 + 2\mu(\chi_e)$ with $\mu(\chi_e) = \frac{\alpha}{\pi\chi_e} \int_0^\infty \frac{y}{(1+y)^3} \mathbf{L1}/3 \left(\frac{2y}{3\chi_e} \right) dy$, we have $g \approx 2.00232$ when $\chi_e \ll 1$. The circularly polarized laser induces a phase shift in the spin precession—due to the anomalous magnetic moment ($g \neq 2$)—which is visible in the phase difference between $E_{y'}$ and $S_{y'}$ in Fig. 3 (c). Although small, this shift is critical: it breaks the symmetry between spin and orbital motion, enabling efficient conversion from transverse to longitudinal polarization, as reflected in the synchronous evolution of $S_\perp$ and $S_\parallel$ in Fig. 3 (c3). The spin dynamics follow the precession equation, where the χ_e -dependence of the g -factor is essential. In our moderate- χ_e regime, g slightly exceeds 2; if g were exactly 2, the spin would precess synchronously with the momentum, suppressing polarization conversion [see the $g = 2$ case in Fig. 3 (c3)]. Simultaneously, positrons gain energy via direct laser acceleration. The laser's asymmetric electric field imparts a transverse drift along y' [see $p_{y'}$ in Fig. 3 (c2)], and the $\mathbf{v} \times \mathbf{B}$ force rotates this motion efficiently along the propagation direction. The essential role of the $\mathbf{v} \times \mathbf{B}$ term is confirmed by control simulations where it is disabled, leading to enhanced $p_{y'}$ and negligible $p_{z'}$ [Fig. 3(c2)].

Under realistic conditions with RR and a tightly focused laser beam [Fig. 3(d)], radiative energy losses damp

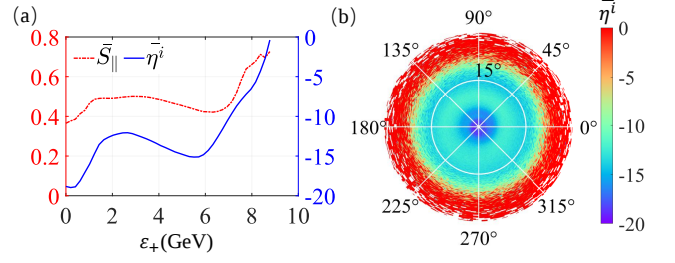


FIG. 4. (a) Final longitudinal polarization $\bar{S}_\parallel$ (red dash-dotted) and creation phase $\bar{\eta}^i$ (blue solid) vs energy ϵ_+ . (b) Birth phase distribution for positrons in Fig. 2(b).

the transverse momentum of the newborn positron, enabling its capture by the laser field [see Fig. 3(d1)]. This RR-mediated momentum reduction allows the positrons to be reflected and confined. The tightly focused geometry creates an asymmetric field that ensures sustained interaction before the positrons escape [see Fig. 3(d2)]. This capture-acceleration mechanism is distinctive in three key aspects: (i) tight integration with positron generation via QED cascades; (ii) constructive use of RR for particle capture, turning a typically detrimental effect into a beneficial tool; (iii) first demonstration of multi-GeV direct laser acceleration of positrons born within the pulse, with simultaneous longitudinal polarization via spin precession. Longer capture durations at higher energies further enhance the longitudinal polarization $S_\parallel$, which depends strongly on the birth laser phase [Fig. 4(a)]. Significant radiation losses suppress kinetic energy, maintaining laser-field dominance over positron

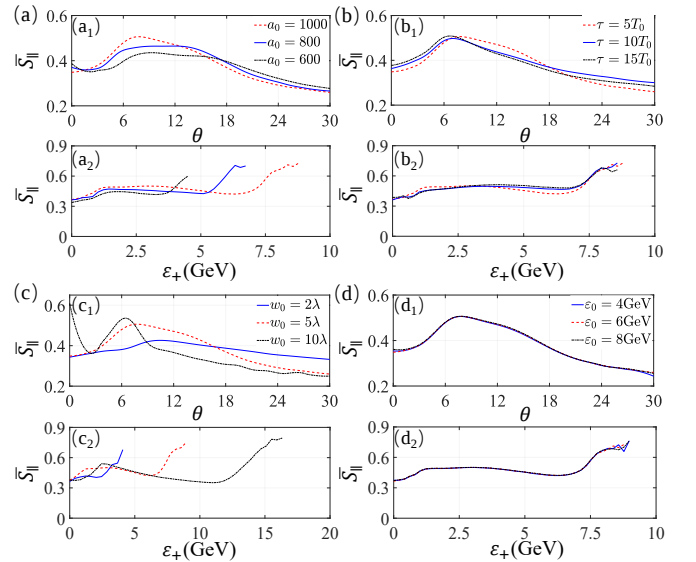


FIG. 5. Profile curves of $\bar{S}_\parallel$ vs θ in $\phi = 0^\circ$ and $\bar{S}_\parallel$ vs energy ϵ_+ in $\theta \in [0, 12^\circ]$ with different laser intensity a_0 (a), laser pulse duration τ (b), laser focal radius w_0 (c) and initial seed electron energy ϵ_0 (d). Other parameters are the same as those in Fig. 2.

dynamics. Both the energy spectrum and angular distribution also exhibit strong phase dependence, as shown in Fig.4(b).

We systematically examine the parameter dependence of the average longitudinal polarization $\bar{S}_{\parallel}$ in Fig.5. Increasing laser intensity (a_0 from 600 to 1000) enhances both positron energy and polarization due to stronger electromagnetic fields [Fig.5(a)], with corresponding yields of 14.6, 20.5, 25.8 e^+/e^- respectively. The polarization shows weak dependence on the pulse duration over the range $5T_0$ to $15T_0$ [Fig.5(b)], consistent with the fact that the positron's final state is governed by the peak laser intensity [40]. Varying the laser focal radius (w_0 from $2\lambda_0$ to $10\lambda_0$) alters the polarization distribution, as it modifies the field phase sampled by the positrons; a larger radius also promotes higher acceleration and energy gain [Fig.5(c)]. Changes in the seed electron energy (ε_0) have a negligible effect on polarization [Fig.5(d)]: radiation-dominated reflection dynamics render the process insensitive to initial energy. However, ε_0 strongly influences the positron yield via the parent photon spectrum, increasing from 17.0 to 25.8 to 34.7 e^+/e^- at $\varepsilon_0 = 4, 6$, and 8 GeV respectively.

In conclusion, we have demonstrated a compact all-optical scheme that simultaneously resolves the long-standing challenges of yield, energy, and polarization in laser-driven positron beam generation. Our approach integrates positron production via a QED cascade, multi-GeV acceleration, and spin manipulation into a single laser-electron collision stage. By leveraging radiation reaction to capture newborn positrons within the laser field, direct laser acceleration boosts them to GeV energies while intrinsic spin precession rotates their polarization to the longitudinal direction. The resulting beams achieve unprecedented performance: a high yield of 25.8 e^+/e^- , energies up to 9 GeV, and longitudinal polarization exceeding 70%. With a feasible seed electron beam density of 10^8 per bunch [38], this setup produces 10^9 positrons per shot. Employing ultrahigh-charge (~ 100 nC) electron beams [45] further enables positron densities of $\sim 10^{12}$ per bunch, meeting the requirements of future colliders and fundamental physics experiments. This work thereby establishes a promising platform for highly polarized positron sources applicable to studies of chiral dynamics and new physics beyond the Standard Model.

ACKNOWLEDGEMENTS

This work is supported by the National Natural Science Foundation of China (Grants nos.12222507 and 12075187), the Strategic Priority Research Program of the Chinese Academy of Sciences (Grants nos. XDA25031000 and No.XDA25010300).

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