

## Polarized Positron Beams via Intense Two-Color Laser Pulses

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The generation of ultrarelativistic polarized positrons during the interaction of an ultrarelativistic electron beam with a counterpropagating two-color petawatt laser pulse is investigated theoretically. Our Monte Carlo simulation, based on a semiclassical model, incorporates photon emissions and pair productions, using spin-resolved quantum probabilities in the local constant field approximation, and describes the polarization of electrons and positrons for the pair production and photon emission processes, as well as the classical spin precession in between. The main reason for the polarization is shown to be the spin asymmetry of the pair production process in strong external fields, combined with the asymmetry of the two-color laser field. Employing a feasible scenario, we show that highly polarized positron beams, with a polarization degree of  $\zeta \approx 60\%$ , can be produced in a femtosecond timescale, with a small angular divergence,  $\sim 74$  mrad, and high density,  $\sim 10^{14}$  cm<sup>-3</sup>. The laser-driven polarized positron source raises hope for providing an alternative for high-energy physics studies.

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Relativistic beams of polarized positrons have important applications in high-energy physics, and solid-state physics. They are powerful probes for precise measurements of the nucleon spin structure [1,2], for determining the electroweak mixing angle [3], and for studying magnetic properties and structural defects of materials [4,5], as well as to test the standard model in the future International Linear Collider (ILC) [6]. A key element for the physics capability of ILC is the ability to provide intense ( $3 \times 10^{10}$ /bunch) highly polarized electron ( $> 80\%$  polarization) and positron (30%–60% polarization) sources [7–10]. While there are several methods for electron polarization [11–15], it is much more demanding to obtain polarized positron beams. For the latter, a two step method has been commonly applied. First, circularly polarized  $\gamma$  photons are produced, and they are then converted to polarized positrons via pair production in a high- $Z$  target. Polarized  $\gamma$  photons can be generated by Compton back-scattering [16,17] or a helical undulator [18–21]. However, all of the existing schemes require challenging technical upgrades to reach the ILC target parameters [9,22,23].

Recent developments of strong laser techniques, see, e.g., Refs. [24–26], have raised hope for polarizing electrons and positrons with laser fields. However, unfortunately the laser field has an oscillating character, changing the field direction in subsequent field cycles. As a consequence, in a monochromatic laser field, the polarization of a particle due to nonlinear Compton scattering is vanishing [27–29] and is small in the case of a short laser pulse [30]. Recent progress in the theory shows that significant polarization for electrons can be acquired in a rotating

electric field [31,32], which models antinodes of a circularly polarized standing laser wave. However, the electrons cannot be trapped in antinodes of a circularly polarized standing wave [33]. In another development, it has been shown recently [34] that with a fine-tuning of the ellipticity of the symmetric laser field, the splitting of the particle beam with respect to polarization can be achieved due to spin-dependent radiation reaction. The same scheme is employed in the pair production regime to split the created positrons with respect to polarization [35].

The petawatt laser technology [36–39] enables another potential method to produce polarized positrons via the multiphoton Breit-Wheeler process [40], when  $e^-e^+$  pairs are produced due to a high-energy  $\gamma$  photon interacting with a strong laser field, accompanied by multiple photon absorption from a strong laser field (first demonstrated in the famous SLAC experiment E-144 [41]). Recently unpolarized electron-positron jets were generated in laser-solid [42–44], and in laser-electron beam interactions [45].

Generally, the radiative polarization of electrons (positrons) requires asymmetric laser fields, but remarkably, as shown here, with a given asymmetric field the spin-dependent asymmetry is stronger for pair production than for photon emission. Consequently, the polarization of the electrons (positrons) during pair production in that field generally will outstrip the radiative polarization. In previous studies [46–48], spin-polarization effects in the multiphoton Breit-Wheeler process have been considered in plane wave laser fields mostly of moderate intensity. It remained unclear if sizable polarization of positrons in realistic strong laser fields is feasible. Photon polarization

effects in nonlinear QED, however, with averaging over the spin of electrons (positrons) have been discussed in Ref. [49].

In this Letter, we investigate theoretically the feasibility of production of collimated and highly polarized ultrarelativistic positron beams during interaction of an ultrarelativistic electron beam with a counterpropagating two-color intense laser pulse in the quantum radiation dominated regime; see the setup in Fig. 1. During the interaction,  $\gamma$  photons via nonlinear Compton scattering are generated, which subsequently decay into electron-positron pairs via the multiphoton Breit-Wheeler process. With Monte Carlo simulations, we study the spin-resolved dynamics of electrons and positrons during pair production and photon emission processes, as well as during propagation in the laser field. In our scheme, positrons are mostly polarized due to the intrinsic asymmetry of spin-resolved pair production probability in strong fields, combined with the asymmetry of the two-color laser field configuration. As a result, an ultrarelativistic positron beam with 60% polarization, with uniformly distributed polarization within the divergence angle, can be generated with realistic laser fields.

We employ a semiclassical Monte Carlo method [50–52] to describe the electron (positron) spin-resolved dynamics in a strong laser field. Photon emission and pair production are simulated via spin-resolved quantum probabilities, derived with the QED operator method under the local constant field approximation (LCFA) [53]; see the details in the Supplemental Material [54]. The LCFA has been widely employed in strong-field QED studies [50–53] and is applicable when the formation length of the process is much smaller than the laser wavelength and the typical size of the electron trajectory [40,55]. In a laser field, the latter requires  $\xi \equiv |e|E_0/(m\omega) \gg 1$ , with the invariant field parameter  $\xi$ , the laser field amplitude  $E_0$ , and the frequency  $\omega$ , while  $e$  and  $m$  are the electron charge and mass, respectively (relativistic units with  $\hbar = c = 1$  are used throughout). The LCFA can fail in describing the low-energy part of the radiation spectrum [56–59] and high-energy asymptotics of radiative corrections [60], which are,

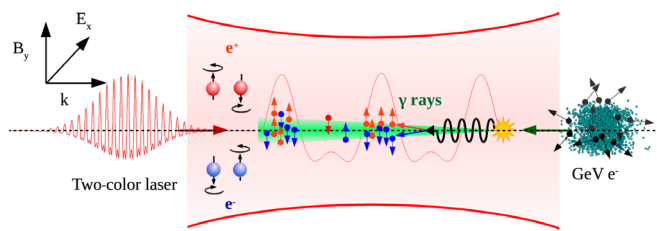


FIG. 1. Scheme of laser-based polarized positron beam production. An intense linearly polarized two-color laser pulse collides head-on with an unpolarized relativistic electron beam, resulting in emission of  $\gamma$  photons in a forward direction which decay into polarized  $e^+$  and  $e^-$ , with spin parallel and antiparallel to the laser’s magnetic field direction, respectively, and with a small divergence angle in the propagation direction.

however, beyond the scope of this Letter; see the Supplemental Material [54]. In our Monte Carlo algorithm, the probabilities are combined with the statistical event generator to determine whether or not a photon emission or pair production process occurs. If a photon is emitted or an electron-positron pair is created, the spins of the particles after the process are determined with respect to the instantaneous spin quantization axis along the rest frame magnetic field [61], employing the corresponding spin-resolved probabilities within the statistical procedure [34,35] (applied recently also in Ref. [62]). Between emission points, the particles are driven classically via the Lorentz force and the spin dynamics is described with the Bargmann-Michel-Telegdi equation [63–65]. The accuracy of our Monte Carlo code is confirmed by reproducing previous results on radiative polarization [15,30,32,34,66] and pair production [35,67,68]; see the Supplemental Material [54].

We consider interaction of an intense two-color linearly polarized laser pulse with a counterpropagating ultrarelativistic electron beam; see Fig. 1. The field consists of two copropagating laser pulses of  $\lambda_1 = 1 \mu\text{m}$  and  $\lambda_2 = 0.5 \mu\text{m}$  wavelengths, and  $\tau_{p1} = 10T_1$  and  $\tau_{p2} = 20T_2$  pulse durations, respectively. The peak amplitudes of each field,  $E_{01}$  and  $E_{02}$ , fulfill the ratio  $R \equiv E_{01}/E_{02} = 2$ , i.e.,  $\xi_1/\xi_2 = 4$  for the field parameters. We use  $\xi_1, \xi_2 \gg 1$  when the LCFA is applicable [54], and comparisons with an improved LCFA code [57] have shown only negligible amendments. The phase difference between the two-color fields is chosen as  $\Delta\phi = 0$  to obtain the maximum field asymmetry. The beam waist size is  $5\lambda_1$  for both laser pulses. The electron beam of a cylindrical form has a longitudinal uniform distribution and transverse Gaussian distribution, with a standard deviation  $\sigma = 0.4\lambda_1$  and beam length  $L_e = 10\lambda_1$ ; the number of electrons in the bunch is  $N_e = 10^6$ . The initial kinetic energy spread of the electron bunch is  $\Delta\epsilon/\epsilon_0 = 0.02$ , and the angular divergence is 1 mrad.

When choosing the laser intensity and the electron energy, we take into account that the pair production is substantial when the quantum field parameter  $\chi_\gamma \gtrsim 1$ , where  $\chi_{\gamma,e} = |e|\hbar\sqrt{-(F_{\mu\nu}p_{\gamma,e}^\nu)^2}/m^3$ , with  $p_{\gamma,e}$  being the 4-momentum of the  $\gamma$  photon and the electron, respectively, and  $F_{\mu\nu}$  the total field tensor, which includes the total field of the two laser fields. One may assume that, during nonlinear Compton scattering, photon and electron energies are of the same order and may estimate  $\chi_\gamma \sim \chi_e$ .

As the presently available laser intensities do not exceed  $10^{22} \text{ W/cm}^2$  [24], and for the electron energies via laser wakefield acceleration, the electron energy is less than 10 GeV [69]; we choose as typical parameters the initial electron energy  $\epsilon_0 = 2 \text{ GeV}$  and the laser full intensity parameter  $\xi_0 = \xi_1 + \xi_2 = 83$ . The produced positron beam parameters are summarized in Fig. 2. The total number of produced positrons is  $N_+ \sim 2 \times 10^4$ , and they travel in a

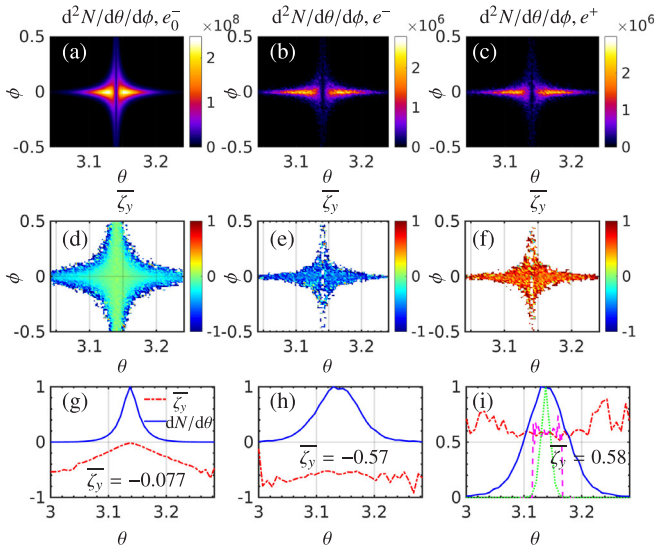


FIG. 2. (Top row) Angular distribution  $d^2N/(d\theta d\phi)$ , with the polar angle  $\theta$  (rad), and the azimuthal angle  $\phi$  (rad) (a) for seed electrons  $e_0^-$ , (b) for produced electrons  $e^-$ , and (c) for positrons  $e^+$ . (Middle row) The averaged spin distribution along the magnetic field direction  $\bar{\zeta}_y$  vs  $\theta$  and  $\phi$  (d) for  $e_0^-$ , (e) for  $e^-$ , and (f) for  $e^+$ . (Bottom row) The particle number distribution  $dN/d\theta$  (solid blue lines), and the average spin component  $\bar{\zeta}_y$  (dashed-dotted red lines): (g) for  $e_0^-$ , (h) for  $e^-$ , and (i) for  $e^+$ . In (i),  $dN/d\theta$  (green line) and  $\bar{\zeta}_y$  (magenta line) are for  $e^+$  at the production points [the beam average of  $\bar{\zeta}_y$  are indicated on panels (g)–(i); the beam average of  $\bar{\zeta}_y$  at the production points is  $\bar{\zeta}_{y0} = 0.6$ ];  $\xi_0 = 83$ ,  $\epsilon_0 = 2$  GeV.

forward direction, with the full width at half maximum (FWHM) of the angular distribution  $\theta_+ \approx 74$  mrad; see Figs. 2(c) and 2(i). The average spin component of the produced positrons along the magnetic field direction (y axis) has a nearly uniform angular distribution ( $\bar{\zeta}_y = 0.58$ ) within the FWHM; see Figs. 2(f) and 2(i). The angle independence of the positron beam polarization renders further collimation feasible without polarization damage. The produced electrons have similar properties as positrons but the opposite sign for polarization; see Figs. 2(b), 2(e), and 2(h). The seed electrons have a narrower angular distribution, as shown in Figs. 2(a) and 2(g), but the polarization degree is significantly lower,  $\bar{\zeta}_y = -0.077$ , than that of the produced  $e^-e^+$  pairs. The latter indicates that the polarization mechanisms for the seed electrons and created particles are different.

To elucidate the reason for the significant polarization of positrons in the two-color laser field, we compare the spin dynamics in one- and two-color laser fields with  $\xi_0 = 83$  in Fig. 3(a). It can be seen that the polarization of seed electrons oscillates in the laser fields for both cases, but only in the two-color field do seed electrons acquire a small  $\bar{\zeta}_y$ . The reason is the almost complete symmetry in the laser magnetic field direction in the case of a single color field, and its asymmetry in the two-color field. After each photon

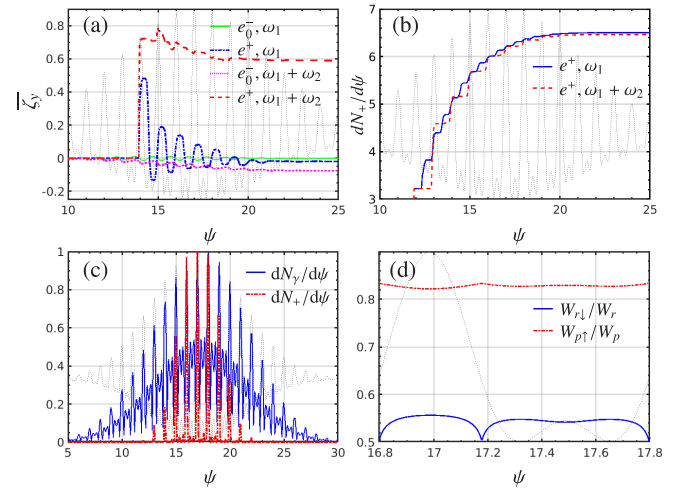


FIG. 3. (a) Averaged spin  $\bar{\zeta}_y$  vs laser cycle  $\psi$ : in a one-color laser pulse, for seed electrons  $e_0^-$  (solid green line) and positrons  $e^+$  (dashed-dotted blue line); in a two-color laser pulse,  $e_0^-$  (dotted pink line) and  $e^+$  (dashed red line). (b) Positron number  $dN/d\psi$  vs  $\psi$  for one- (solid blue line) and two-color (dashed red line) laser pulses. (c) Photon number  $dN_\gamma/d\psi$  emitted by  $e_0^-$  (solid blue line) and positron number  $dN_+/d\psi$  (dashed red line) at production points. (d) Ratio of electron radiation probability with spin antiparallel to the magnetic field direction (solid blue line), and ratio of pair production probability with the positron spin parallel to magnetic field direction (dashed-dotted red line);  $\xi_0 = 83$ ,  $\epsilon_0 = 2$  GeV. The faint dotted line is the two-color laser field.

emission, the electrons (positrons) are more likely to flip opposite to (along) the magnetic field direction in the particle rest frame, which is approximately parallel (antiparallel) to the magnetic field direction  $B_y$  for electrons (positrons) in the lab frame. This is because the spin-resolved emission probability is in favor of spin-down for electrons. As shown in Fig. 3(d),  $W_{r\downarrow}/W_r > 50\%$ , where  $W_r$  is the radiation total probability and  $W_{r\downarrow}$  is the probability with the final spin antiparallel to the magnetic field. Therefore,  $\bar{\zeta}_y$  of seed electrons increases during  $B_y < 0$  and decreases during  $B_y > 0$ ; see Fig. 3(a). In the one-color laser pulse,  $\bar{\zeta}_y$  oscillates symmetrically in consecutive laser cycles and levels off to zeros after the interaction. While the two-color field breaks this symmetric pattern in  $\bar{\zeta}_y$  oscillation, more electrons emit photons and acquire  $\zeta_y < 0$  during  $B_y > 0$ , which results in a  $-7.7\%$  polarization at the end of the interaction; see Fig. 3(a).

Unlike the seed electrons that are slightly polarized due to radiative polarization, the produced positrons (electrons) are highly polarized  $\bar{\zeta}_y \sim 60\%$ ; see Fig. 2(i). Although the polarization of both seed electrons and created pairs benefits from the asymmetry of the two-color field configuration, the asymmetry has a more significant impact on the polarization of the pairs than on the seed electrons. This is because seed electrons are polarized by radiative polarization due to photon emissions, while the pair polarization

comes mainly from the creation process. There are two reasons for spin asymmetry in the pair production process in an asymmetric field. First, the spin related terms in the probabilities play a more important role in the case of pair production than in radiation, as shown in Fig. 3(d). It is much more likely to have a positron along the magnetic field during the pair production process (around 80%) than due to photon emission (around 55%). Second, the probability of the pair production has a stronger dependence on the laser intensity than the radiation probability. As shown in Fig. 3(c), the pair production takes place mainly in the dominant half-cycles of the two-color field and is fully suppressed in the weak half-cycle, while photons are emitted in both half-cycles with slightly different probabilities. The latter is the main reason for highly polarized positrons in a two-color field.

Since positrons are more likely to be produced along the instantaneous laser magnetic field, in a one-color symmetric laser field, the averaged polarization is negligible after the interaction, as shown in Fig. 3(a). However, in the two-color asymmetric field, a large polarization for the positron beam is obtained because positrons are mostly produced at  $B_y > 0$  [see Figs. 3(b) and 3(c)], and the probability of these positrons being polarized with  $\zeta_y > 0$  is very large [see Fig. 3(d)]. Therefore, the positron density for  $\zeta_y > 0$  is far higher than that for  $\zeta_y < 0$ .

We underline the fact that the positron initial polarization degree during the production process further decreases due to photon emissions. This is because the radiative polarization has less spin dependence than the pair production, according to Fig. 3(d). Positrons produced with  $\zeta_y > 0$  have a chance to flip to  $\zeta_y < 0$  when emitting photons at  $B_y < 0$ , which brings down the polarization. Fortunately, the decrease of the polarization degree is not large, ranging from  $\bar{\zeta}_y \sim 60\%$  at the production point to the final  $\bar{\zeta}_y \sim 58\%$ , as is shown in Fig. 2(i).

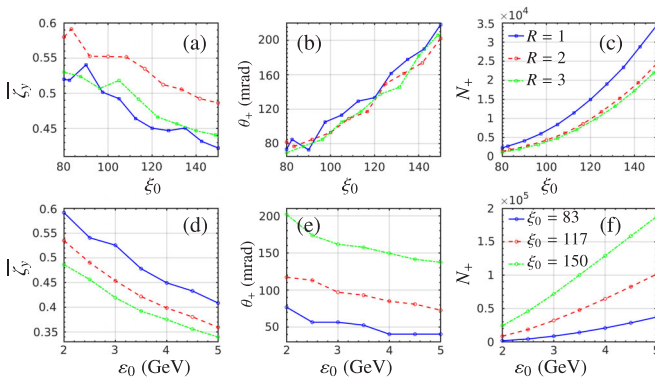


FIG. 4. (a),(d) The averaged polarization  $\bar{\zeta}_y$ . (b),(e) FWHM of  $\theta_+$  and (c),(f) the positron number  $N_+$ . (Top row)  $R = 1$  (solid blue lines),  $R = 2$  (dashed red lines), and  $R = 3$  (dotted-dashed green lines) vs laser peak intensity  $\xi_0$  for  $\epsilon_0 = 2$  GeV. (Bottom row)  $\xi_0 = 83$  (solid blue lines),  $\xi_0 = 117$  (dashed red lines), and  $\xi_0 = 150$  (dotted-dashed green lines) for  $R = 2$ . The number of initial electrons is  $N_- = 2 \times 10^5$ .

We have investigated the optimal conditions for positron polarization, and the results are summarized in Fig. 4. First, we varied the ratio ( $R$ ) of laser intensities. Figure 4(a) shows that  $R = 2$  is the optimal choice of relative laser intensities to obtain higher polarization. In fact, in this case, the two-color field is most asymmetric when the  $B_y < 0$  parts of the field reach minimum strength. Increasing laser intensity yields more pairs [see Fig. 3(c)] but reduces the averaged polarization and increases angular divergence [see Figs. 3(a) and 3(b)]. This is because higher laser intensity triggers more pair production in negative parts of laser fields, bringing in more positrons with  $\zeta_y < 0$ . The similar scaling laws can also be found for electrons' initial energy; see Figs. 4(c) and 4(d). More energetic electrons give rise to more pairs and better emittance but compromise the polarization degree. If high polarization has priority over positron density, smaller laser intensity and initial electron energy is preferable. If one aims for an intense  $e^+$  beam with a moderate polarization degree, higher laser intensity and more brightness of electrons are preferable.

The number of initial electrons in our simulation is  $10^6$ , which yields a final electron number in the bunch  $10^6$ , and  $10^4$  positrons in the bunch, with 8% and 60% polarization degree, respectively. The available laser wakefield acceleration technique can provide approximately  $10^{10}$  electrons in the GeV regime [69], which will allow for  $10^8$  polarized positrons in the bunch with  $\zeta \approx 60\%$  degree of polarization ( $10^{10}$  electrons per bunch with  $\zeta \approx 8\%$ ). Moreover, since the polarization is inversely proportional to the particles' energy [54], the beam polarization can be increased with an appropriate energy selection. For the positrons with an energy smaller than 200 MeV, which account for 36% of the total positrons, the polarization degree increases from 58% to 70%. The parameters of the laser-driven polarized positron beam—namely, the polarization degree, the number of positrons in a bunch, the energy spread, and the transverse emittance of the beam—are competitive with those of the existing methods for polarized positrons [54]. It raises the hope of permitting applications, in particular for future colliders, when high repetition rates become accessible for petawatt lasers [70,71].

In summary, we have put forward a novel concept of two-color laser-based production of polarized positron beams. It employs an unpolarized electron driver and presently available ultrastrong lasers. The experiment can be conducted by using an electron beam generated by laser wakefield accelerated electrons head-on colliding with a two-color laser pulse. In contrast to known radiative polarization, the polarization of positrons during their creation in the laser field is shown to be much more sensitive to the field asymmetry and allows for a high degree of polarization. The produced positrons may advance the capacity of detection techniques in solid-state and nuclear physics by providing additional spin

information, and they may encourage the realization of polarized positron beams in a future linear collider.

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*Note added.*—Recently radiative polarization via two-color fields was further extended in Refs. [72,73]. The systematic studies provide optimized parameters with regard to maximal radiative polarization.

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- [1] A. V. Subashiev, Yu. P. Yashin, J. E. Clendenin, and Yu. A. Mamaev, Spin polarized electrons: Generation and applications, *Phys. Low Dimens. Struct.* **1**, 1 (1998) [SLAC PUB 8035 (1998)].
- [2] E. Voutier, Physics potential of polarized positrons at the Jefferson Laboratory, in *Proceedings of the XXXIII International Workshop on Nuclear Theory, Rila, Bulgaria, 2014*, edited by A. Georgieva and N. Minkov (Heron Press, Sofia, Bulgaria, 2014), p. 142.
- [3] P. L. Anthony, R. G. Arnold, C. Arroyo, K. Bega, J. Biesiada, P. E. Bosted, G. Bower, J. Cahoon, R. Carr, G. D. Cates *et al.*, Precision Measurement of the Weak Mixing Angle in Moeller Scattering, *Phys. Rev. Lett.* **95**, 081601 (2005).
- [4] D. W. Gidley, A. R. Köymen, and T. Weston Capehart, Polarized Low-Energy Positrons: A New Probe of Surface Magnetism, *Phys. Rev. Lett.* **49**, 1779 (1982).
- [5] R. Krause-Rehberg and H. S. Leipner, *Positron Annihilation in Semiconductors: Defect Studies*, Springer Series in Solid-State Sciences Vol. 127 (Springer Science+Business Media, New York, 1999).
- [6] K. Fujii, D. J. Miller, and A. Soni, *Linear Collider Physics in the New Millennium*, Advanced Series On Directions In High Energy Physics Vol. 19 (World Scientific, Singapore, 2005).
- [7] G. Moortgat-Pick, T. Abe, G. Alexander, B. Ananthanarayan, A. A. Babich, V. Bharadwaj, D. Barber, A. Bartl, A. Brachmann, S. Chen *et al.*, Polarized positrons and electrons at the linear collider, *Phys. Rep.* **460**, 131 (2008).
- [8] A. Vauth and J. List, Beam polarization at the ILC: Physics case and realization, *Int. J. Mod. Phys. A* **40**, 1660003 (2016).
- [9] D. J. Scott, J. A. Clarke, D. E. Baynham, V. Bayliss, T. Bradshaw, G. Burton, A. Brummitt, S. Carr, A. Lintern, J. Rochford *et al.*, Demonstration of a High-Field Short-Period Superconducting Helical Undulator Suitable for Future TeV-Scale Linear Collider Positron Sources, *Phys. Rev. Lett.* **107**, 174803 (2011).
- [10] J. A. Clarke, L. I. Malysheva, R. Dollan, J. B. Dainton, J. Sheppard, W. T. Piggott, W. Gai, J. Gronberg, A. A. Mikhailichenko, A. F. Hartin *et al.*, The design of the positron source for the International Linear Collider, *Conf. Proc.* **C0806233**, WEOBG03 (2008).
- [11] D. T. Pierce and F. Meier, Photoemission of spin-polarized electrons from GaAs, *Phys. Rev. B* **13**, 5484 (1976).
- [12] A. A. Sokolov and I. M. Ternov, On polarization and spin effects in the theory of synchrotron radiation, *Sov. Phys. Dokl.* **8**, 1203 (1964).
- [13] A. A. Sokolov and I. M. Ternov, *Synchrotron Radiation* (Akademie, Berlin, 1968).
- [14] V. N. Baier and V. M. Katkov, Radiational polarization of electrons in inhomogeneous magnetic field, *Phys. Lett.* **24A**, 327 (1967).
- [15] V. N. Baier, Radiative polarization of electrons in storage rings, *Sov. Phys. Usp.* **14**, 695 (1972).
- [16] I. Sakai, T. Aoki, K. Dobashi, M. Fukuda, A. Higurashi, T. Hirose, T. Imura, Y. Kurihara, T. Okugi, T. Omori, J. Urakawa, M. Washio, and K. Yokoya, Production of high brightness  $\gamma$  rays through backscattering of laser photons on high-energy electrons, *Phys. Rev. ST Accel. Beams* **6**, 091001 (2003).
- [17] T. Omori, M. Fukuda, T. Hirose, Y. Kurihara, R. Kuroda, M. Nomura, A. Ohashi, T. Okugi, K. Sakaue, T. Saito *et al.*, Efficient Propagation of Polarization from Laser Photons to Positrons Through Compton Scattering and Electron-Positron Pair Creation, *Phys. Rev. Lett.* **96**, 114801 (2006).
- [18] G. Alexander, J. Barley, Y. Batygin, S. Berridge, V. Bharadwaj, G. Bower, W. Bugg, F.-J. Decker, R. Dollan, Y. Efremenko *et al.*, Observation of Polarized Positrons from an Undulator-Based Source, *Phys. Rev. Lett.* **100**, 210801 (2008).
- [19] G. Alexander, J. Barley, Y. Batygin, S. Berridge, V. Bharadwaj, G. Bower, W. Bugg, F.-J. Decker, R. Dollan, Y. Efremenko *et al.*, Undulator-based production of polarized positrons, *Nucl. Instrum. Methods Phys. Res., Sect. A* **610**, 451 (2009).
- [20] G. Alexander, Undulator-based production of polarized positrons, a proposal for the 50-GeV beam in the FFTB, Stanford Linear Accelerator Center Report No. SLAC-TN-04-018, 2004.
- [21] A. W. Weidemann (E-166 Collaboration), Polarized positrons at a future linear collider and the final focus test beam, *Int. J. Mod. Phys. A* **20**, 7423 (2005).
- [22] B. C. Barish, The baseline configuration for the ILC, ICFA Beam Dyn. Newsletter **40**, 8 (2006).
- [23] C. Adolphsen, M. Barone, B. Barish, K. Buesser, P. Burrows, J. Carwardine, J. Clark, H. M. Durand, G. Dugan, E. Elsen *et al.*, The International Linear Collider technical design report—Volume 3. II: Accelerator baseline design, [arXiv:1306.6328](https://arxiv.org/abs/1306.6328).
- [24] J. W. Yoon, C. Jeon, J. Shin, S. K. Lee, H. W. Lee, I. W. Choi, H. T. Kim, J. H. Sung, and C. H. Nam, Achieving the laser intensity of  $5.5 \times 10^{22}$  w/cm<sup>2</sup> with a wavefront-corrected multi-PW laser, *Opt. Express* **27**, 20412 (2019).
- [25] A. Kessel, V. E. Leshchenko, O. Jahn, M. Krüger, A. Münzer, A. Schwarz, V. Pervak, M. Trubetskov, S. A. Trushin, F. Krausz, Z. Major, and S. Karsch, Relativistic few-cycle pulses with high contrast from picosecond-pumped OPCPA, *Optica* **5**, 434 (2018).
- [26] See <https://www.clf.stfc.ac.uk/Pages/The-Astra-Gemini-Facility.aspx>.
- [27] G. L. Kotkin, V. G. Serbo, and V. I. Telnov, Electron (positron) beam polarization by Compton scattering on

- circularly polarized laser photons, *Phys. Rev. ST Accel. Beams* **6**, 011001 (2003).
- [28] D. Yu. Ivanov, G. L. Kotkin, and V. G. Serbo, Complete description of polarization effects in emission of a photon by an electron in the field of a strong laser wave, *Eur. Phys. J. C* **36**, 127 (2004).
- [29] D. V. Karlovets, Radiative polarization of electrons in a strong laser wave, *Phys. Rev. A* **84**, 062116 (2011).
- [30] D. Seipt, D. Del Sorbo, C. P. Ridgers, and A. G. R. Thomas, Theory of radiative electron polarization in strong laser fields, *Phys. Rev. A* **98**, 023417 (2018).
- [31] D. Del Sorbo, D. Seipt, T. G. Blackburn, A. G. R. Thomas, C. D. Murphy, J. G. Kirk, and C. P. Ridgers, Spin polarization of electrons by ultraintense lasers, *Phys. Rev. A* **96**, 043407 (2017).
- [32] D. Del Sorbo, D. Seipt, A. G. R. Thomas, and C. P. Ridgers, Electron spin polarization in realistic trajectories around the magnetic node of two counter-propagating, circularly polarized, ultra-intense lasers, *Plasma Phys. Controlled Fusion* **60**, 064003 (2018).
- [33] A. V. Bashinov, P. Kumar, and A. V. Kim, Particle dynamics and spatial  $e^-e^+$  density structures at QED cascading in circularly polarized standing waves, *Phys. Rev. A* **95**, 042127 (2017).
- [34] Y.-F. Li, R. Shaisultanov, K. Z. Hatsagortsyan, F. Wan, C. H. Keitel, and J.-X. Li, Ultrarelativistic Electron Beam Polarization in Single-Shot Interaction with an Ultraintense Laser Pulse, *Phys. Rev. Lett.* **122**, 154801 (2019).
- [35] F. Wan, R. Shaisultanov, Y.-F. Li, K. Z. Hatsagortsyan, C. H. Keitel, and J.-X. Li, Ultrarelativistic polarized positron jets via collision of electron and ultraintense laser beams, [arXiv:1904.04305](https://arxiv.org/abs/1904.04305).
- [36] C. Danson, D. Hillier, N. Hopps, and D. Neely, Petawatt class lasers worldwide, *High Power Laser Sci. Eng.* **3**, e3 (2015).
- [37] The Vulcan facility, <http://www.clf.stfc.ac.uk/Pages/The-Vulcan-10-Petawatt-Project.aspx>.
- [38] The Extreme Light Infrastructure (ELI), <http://www.eli-beams.eu/en/facility/lasers/>.
- [39] Exawatt Center for Extreme Light Studies (XCELS), <http://www.xcels.iapras.ru/>.
- [40] V. I. Ritus, Quantum effects of the interaction of elementary particles with an intense electromagnetic field, *J. Sov. Laser Res.* **6**, 497 (1985).
- [41] D. L. Burke, R. C. Field, G. Horton-Smith, J. E. Spencer, D. Walz, S. C. Berridge, W. M. Bugg, K. Shmakov, A. W. Weidemann, C. Bula *et al.*, Positron Production in Multiphoton Light-by-Light Scattering, *Phys. Rev. Lett.* **79**, 1626 (1997).
- [42] H. Chen, S. C. Wilks, J. D. Bonlie, E. P. Liang, J. Myatt, D. F. Price, D. D. Meyerhofer, and P. Beiersdorfer, Relativistic Positron Creation Using Ultraintense Short Pulse Lasers, *Phys. Rev. Lett.* **102**, 105001 (2009).
- [43] H. Chen *et al.*, Relativistic Quasimonoeenergetic Positron Jets from Intense Laser-Solid Interactions, *Phys. Rev. Lett.* **105**, 015003 (2010).
- [44] E. Liang, T. Clarke, A. Henderson, W. Fu, W. Lo, D. Taylor, P. Chaguine, S. Zhou, Y. Hua, X. Cen, X. Wang, J. Kao, H. Hasson, G. Dyer, K. Serratto, N. Riley, M. Donovan, and T. Ditmire, High  $e^+e^-$  ratio dense pair creation with  $10^{21}$  W.cm<sup>-2</sup> laser irradiating solid targets, *Sci. Rep.* **5**, 13968 (2015).
- [45] G. Sarri *et al.* Generation of neutral and high-density electron-positron pair plasmas in the laboratory, *Nat. Commun.* **6**, 6747 (2015).
- [46] Y. S. Tsai, Laser +  $e^- \rightarrow \gamma + e^-$  and laser +  $\gamma e^+ + e^-$  as sources of producing circularly polarized  $\gamma$  and  $e^\pm$  beams, *Phys. Rev. D* **48**, 96 (1993).
- [47] D. Yu. Ivanov, G. L. Kotkin, and V. G. Serbo, Complete description of polarization effects in  $e^+e^-$  pair production by a photon in the field of a strong laser wave, *Eur. Phys. J. C* **40**, 27 (2005).
- [48] M. J. A. Jansen, J. Z. Kamiński, K. Krajewska, and C. Müller, Strong-field Breit-Wheeler pair production in short laser pulses: Relevance of spin effects, *Phys. Rev. D* **94**, 013010 (2016).
- [49] B. King, N. Elkina, and H. Ruhl, Photon polarization in electron-seeded pair-creation cascades, *Phys. Rev. A* **87**, 042117 (2013).
- [50] C. P. Ridgers, J. G. Kirk, R. Ducloux, T. G. Blackburn, C. S. Brady, K. Bennett, T. D. Arber, and A. R. Bell, Modelling gamma-ray photon emission and pair production in high-intensity laser-matter interactions, *J. Comput. Phys.* **260**, 273 (2014).
- [51] N. V. Elkina, A. M. Fedotov, I. Yu. Kostyukov, M. V. Legkov, N. B. Narozhny, E. N. Nerush, and H. Ruhl, QED cascades induced by circularly polarized laser fields, *Phys. Rev. ST Accel. Beams* **14**, 054401 (2011).
- [52] D. G. Green and C. N. Harvey, SIMLA: Simulating particle dynamics in intense laser and other electromagnetic fields via classical and quantum electrodynamics, *Comput. Phys. Commun.* **192**, 313 (2015).
- [53] V. N. Baier, V. M. Katkov, and V. M. Strakhovenko, *Electromagnetic Processes at High Energies in Oriented Single Crystals* (World Scientific, Singapore, 1998).
- [54] See Supplemental Materials at <http://link.aps.org/supplemental/10.1103/PhysRevLett.123.174801> for details on the applied theoretical model, and on the simulation results for other laser and electron parameters.
- [55] E. S. Sarachik and G. T. Schappert, Classical theory of the scattering of intense laser radiation by free electrons, *Phys. Rev. D* **1**, 2738 (1970).
- [56] A. Di Piazza, M. Tamburini, S. Meuren, and C. H. Keitel, Implementing nonlinear Compton scattering beyond the local-constant-field approximation, *Phys. Rev. A* **98**, 012134 (2018).
- [57] A. Di Piazza, M. Tamburini, S. Meuren, and C. H. Keitel, Improved local-constant-field approximation for strong-field QED codes, *Phys. Rev. A* **99**, 022125 (2019).
- [58] A. Ilderton, B. King, and D. Seipt, Extended locally constant field approximation for nonlinear Compton scattering, *Phys. Rev. A* **99**, 042121 (2019).
- [59] C. N. Harvey, A. Ilderton, and B. King, Testing numerical implementations of strong-field electrodynamics, *Phys. Rev. A* **91**, 013822 (2015).
- [60] T. Podszus and A. Di Piazza, High-energy behavior of strong-field QED in an intense plane wave, *Phys. Rev. D* **99**, 076004 (2019).
- [61] L. D. Landau and E. M. Lifshitz, *The Classical Theory of Fields* (Elsevier, Oxford, 1975).

- [62] X. S. Geng, L. L. Ji, B. F. Shen, B. Feng, Z. Guo, Q. Q. Han, C. Y. Qin, N. W. Wang, W. Q. Wang, Y. T. Wu *et al.*, Radiative deflection by spin effect in the quantum radiation-reaction regime, [arXiv:1901.10641](https://arxiv.org/abs/1901.10641).
- [63] V. Bargmann, L. Michel, and V. L. Telegdi, Precession of the Polarization of Particles Moving in a Homogeneous Electromagnetic Field, *Phys. Rev. Lett.* **2**, 435 (1959).
- [64] M. W. Walser, D. J. Urbach, K. Z. Hatsagortsyan, S. X. Hu, and C. H. Keitel, Spin and radiation in intense laser fields, *Phys. Rev. A* **65**, 043410 (2002).
- [65] V. I. Ritus, Radiative effects and their enhancement in an intense electromagnetic field, *Sov. Phys. JETP* **30**, 1181 (1970).
- [66] J. D. Jackson, On understanding spin-flip synchrotron radiation and the transverse polarization of electrons in storage rings, *Rev. Mod. Phys.* **48**, 417 (1976).
- [67] A. Gonoskov, S. Bastrakov, E. Efimenko, A. Ilderton, M. Marklund, I. Meyerov, A. Muraviev, A. Sergeev, I. Surmin, and E. Wallin, Extended particle-in-cell schemes for physics in ultrastrong laser fields: Review and developments, *Phys. Rev. E* **92**, 023305 (2015).
- [68] A. A. Sokolov and I. M. Ternov, *Radiation from Relativistic Electrons* (American Institute of Physics, New York, 1986).
- [69] W. P. Leemans, A. J. Gonsalves, H.-S. Mao, K. Nakamura, C. Benedetti, C. B. Schroeder, C. Tóth, J. Daniels, D. E. Mittelberger, S. S. Bulanov *et al.*, Multi-GeV Electron Beams from Capillary-Discharge-Guided Subpetawatt Laser Pulses in the Self-Trapping Regime, *Phys. Rev. Lett.* **113**, 245002 (2014).
- [70] B. Rus, P. Bakule, D. Kramer, G. Korn, J. T. Green, J. N3v3k, M. Fibrich, F. Batysta, J. Thoma, J. Naylon *et al.*, *Proc. SPIE 8780, High-Power, High-Energy, and High-Intensity Laser Technology; and Research Using Extreme Light: Entering New Frontiers with Petawatt-Class Lasers, 87801T* (2013).
- [71] J. Kawanaka, K. Tsubakimoto, H. Yoshida, K. Fujioka, Y. Fujimoto, S. Tokita, T. Jitsuno, and N. Miyanaga (G-EXA Design Team), Conceptual design of sub-exa-watt system by using optical parametric chirped pulse amplification, *J. Phys. Conf. Ser.* **688**, 012044 (2016).
- [72] H.-H. Song, W.-M. Wang, J.-X. Li, Y.-F. Li, and Yu.-T. Li, Spin-polarization effects of ultrarelativistic electron beam in ultraintense two-color laser pulses, *Phys. Rev. A* **100**, 033407 (2019).
- [73] D. Seipt, D. Del Sorbo, C. P. Ridgers, and A. G. R. Thomas, Ultrafast polarization of an electron beam in an intense bi-chromatic laser field, [arXiv:1904.12037](https://arxiv.org/abs/1904.12037).