Trapping and acceleration of spin-polarized positrons from $\gamma$ photon splitting in wakefields

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Energetic spin-polarized positrons are extremely demanded for forefront researches, such as $e^-e^+$ collider physics, but making compact positron sources is still very challenging. Here we put forward an efficient scheme of trapping and acceleration of polarized positrons in plasma wakefields. Seed electrons colliding with a dichromatic laser create polarized $\gamma$ photons which then split into $e^-e^+$ pairs via nonlinear Breit-Wheeler process with an average (partial) positron polarization above 30% (70%). Over 70% positrons are trapped and accelerated in recovered wakefields driven by a hollow electron beam, obtaining an energy gain of 3.5 GeV/cm with slight depolarization. This scheme provides a potential for constructing compact and economical positron sources for future applications.

Plasma-based wakefield accelerators have attracted worldwide attentions in recent years due to their capability of providing acceleration gradients three orders of magnitude higher than conventional radio-frequency accelerators [1–3]. Over the past decades, the wakefield acceleration of electrons has been developed rapidly [4–5]. This promises a new possibility for future electron-positron ($e^-e^+$) colliders with relatively compact size and low cost [6–8]. To this end, trapping and acceleration of polarized positron beams are highly demanded on top of the advantage of high acceleration gradient for electrons in wakefields [9,10]. However, generation, polarization, trapping and acceleration of such positron beams in plasma wakefields are still quite challenging.

Although plenty of schemes [4] have been proposed and studied for the effective trapping and acceleration of electrons in plasma wakefields [11,12], those schemes are not applicable for positrons since the transverse fields in nonlinear wakes usually defocus positrons, which makes continuous positron acceleration impossible. To overcome this issue, an amount of theoretical schemes have been proposed to simultaneously accelerate and focus positrons by using special driver or plasma structures, such as Laguerre-Gaussian laser pulses [13], hollow electron beam drivers [14], and finite-radius plasma columns [15]. But, unfortunately, in those studies the generation and injection of positrons have to be pre-provided. In recent FACET experiments, the positron accelerations have been demonstrated to run in a self-loaded plasma wakefield [16] or a hollow plasma channel [17,18]. However, a pre-accelerated relativistic positron beam is also required and the beam polarization has not been studied yet.

Positrons are commonly polarized either via radiative process (Sokolov-Ternov effect) in a storage ring [19,21] or via high-energy polarized $\gamma$ photons interacting with a high $Z$-target (Bethe-Heitler pair production) [22]. For the former the polarization time is rather long since the magnetic fields of a synchrotron are quite weak; for the latter the positron density is limited by the low photon luminosity [23,24]. Recently, the state-of-the-art laser pulses with peak intensities up to $10^{22}$ W/cm$^2$ [25–29] enable to excite nonlinear quantum electrodynamics (QED) processes [30,31] in laser-matter interaction [32–35]. And, polarized GeV-level positron beams can be created via employing asymmetric spin-resolved probabilities of nonlinear Breit-Wheeler (BW) pair production in a bichromatic [36] or elliptically-polarized laser pulse [37] (transverse polarization; the polarization of intermediate photons was not considered therein), or via the helicity transfer from polarized electrons (longitudinal polarization) [38]. However, in those methods the positron energies are limited by those of the scattering electrons via intermediate photons and impossible to achieve the level of hundreds of GeVs, and the beam qualities, such as the energy spread and emittance, are far worse than those of the beams from conventional accelerators, which severely restrict the applications in high-energy and particle physics (e.g. the polarized $e^-e^+$ collider [10]).

In this Letter, we propose a compact scheme to generate polarized positrons and inject them into plasma wakefields with further acceleration to high energies. The positron generation and polarization are studied quantum mechanically, while the bubble-recovery-based positron trapping and following acceleration and depolarization in wakefields semi-classically. The interaction schematic is shown in Fig. 1. A hollow electron beam working as a wake driver propagates into a low-density plasma and excites nonlinear wakefields (bubbles). Behind it, another copropagating seed electron beam collides with an ultra-intense linearly-polarized (LP) bichromatic laser pulse to emit abundant LP $\gamma$ photons via nonlinear Compton scattering, which could further decay into transversely polarized pairs through nonlinear BW process [see Fig. 1(a)] due to the asymmetric pair production and polarization probabilities in
the laser positive and negative half cycles. We underline that in this study the polarization of intermediate $\gamma$ photons has been taken into account, otherwise the yield and polarization of the positrons will be remarkably overestimated. During the collision of the laser and seed beam, the wake structure driven by the driver beam is first destroyed and then gradually self-recover at the downstream of the laser-seed-beam collision point. Some of the created high-energy polarized positrons can be trapped in the recovered wake fields [see Figs. 1(b1) and (b2)] and then accelerated by the wake fields [see Figs. 1(b3) and (b4)]. In our simulations over 70% positrons are finally injected into the wake and get further acceleration to an average energy beyond 1.2 GeV in 1 millimeter, with an average polarization exceeding 30%. The partial polarization of the positrons within the full width at half maximum (FWHM) of the energy spectrum can exceed 70% [see Fig. 2(c)]. The detailed injection and acceleration processes are discussed in the following.

We develop a Monte Carlo algorithm and implement it into two-dimensional QED particle-in-cell (PIC) code (benchmarked by EPOCH code [59]) to describe the creation and polarization of the pairs quantum mechanically by using spin-resolved probabilities of nonlinear BW pair production [40], which are derived from the QED operator method [31] in the local constant field approximation (valid at the invariant laser field parameter $a_0 = |e|E_0/m \omega \gg 1$) [40] [42] [43]. To efficiently generate $\gamma$ photons and pairs requires the nonlinear QED parameters $\chi_\gamma \equiv |e|\sqrt{-F_{\mu \nu}p^\nu}/m^2 \gtrsim 1$ (for electrons) and $\chi_\gamma \equiv |e|\sqrt{-F_{\mu \nu}k_\gamma^\nu}/m^2 \gtrsim 1$ (for $\gamma$ photons) [40] [42]. Here, $F_{\mu \nu}$ is the field tensor, $p_\mu$ and $k_\gamma^\mu$ the 4-momenta of electron and $\gamma$ photon, respectively, $e$ and $m$ the electron charge and mass, respectively, and $E_0$ and $\omega$ the laser amplitude and frequency, respectively. Relativistic units with $c = \hbar = 1$ are used throughout. The simulations of spin-resolved electron (positron) dynamics and photon emission and polarization follow the semi-classical algorithms in Refs. [37] [45] [46]. See more details of our simulation method in [40].

The simulation parameters of the laser pulse, electron beams and plasma are summarized as follows. A tightly-focused LP Gaussian bichromatic laser pulse propagates along $-z$ direction with $\theta_L = 105^\circ$ and polarizes in $x' - z'$ plane, with wavelengths $\lambda_1 = 1 \mu m$ (period $T_1$) and $\lambda_2 = 5.5 \mu m$, pulse durations $\tau_1 = \tau_2 = 6T_1$, focal radii $w_1 = w_2 = 2 \mu m$, and peak amplitudes $a_1 = 4a_2 = 67$ (corresponding to the peak intensities $I_1 = 4I_2 \approx 6.15 \times 10^{21} \text{W/cm}^2$). An unpolarized elliptical seed beam propagates along $+z$ direction, with an average energy $E_{s,0} = 4 \text{GeV}$, major axis $L_{maj} = 7 \mu m$, and minor axis $L_{min} = 2 \mu m$. A hollow driver beam is initially placed at the entrance of the plasma, with an average energy $E_{d,0} = 1 \text{GeV}$, outer radius $w_{out} = 3 \mu m$, inner radius $w_{in} = 1.5 \mu m$, and length $L_{d} = 9 \mu m$. The density, energy spread and angular divergence of the two electron beams are $n_{s,0} = n_{d,0} = 0.1n_c$, with a Gaussian distribution (the critical density $n_c = 1.1 \times 10^{21} \text{cm}^{-3}$ with respect to the laser pulse with wavelength of $\lambda_1$), $\Delta E_{s0}/E_{s0} = \Delta E_{d0}/E_{d0} = 0.1$, and $\Delta \theta_1 = \Delta \theta_1 = 0.1$ mrad, respectively. Here the delay distance of the two electron beams is $d = 0 \mu m$. More parameter scans for the driver beam size and other effects are shown in Fig. 3. The density of the background plasma (composed of $H^-$ and electrons) is $n_{p,0} = 0.01n_c$. Note that the efficient excitation of a wakefield with central focusing fields for the positrons requires the driver beam satisfying $w_{in}/\sigma_x \geq 3$ and $k_\rho \sigma_z < 2$ [44] [47], where $\sigma_x$ and $\sigma_z$ are the transverse and longitudinal sizes of the driver beam and $k_\rho = 2\pi/\lambda_\rho$ with $\lambda_\rho = \sqrt{mn_e e^2}$. Here we use $w_{in}/\sigma_x = 3$ and $k_\rho \sigma_z \approx 1.8$, and the simulation domain is $60\lambda_1(x) \times 80\lambda_1(z)$ with grid resolutions $dx = dz = \lambda_1/50$.

The main results of the positron trapping, acceleration and polarization are shown in Figs. 2 and 3. The pair production process is completed at the distance of $t_\gamma \approx 40T_1$, where the bubble has not fully recovered yet, and nearly $4 \times 10^9$ positrons are created with a yield ratio $N_+/N_- \approx 0.4\%$ (corresponding to a density of $n_+ \sim 10^{-6}n_c$) and an average polarization (mainly along the magnetic field direction $y$) $S_+ \approx 33.52\%$ [see Fig. 2(a)]. As we mentioned before, if the polarization of intermediate $\gamma$ photons is artificially neglected as usual, $S_+$ will be considerably overestimated by exceeding 68% [see the blue-dash-dotted line in Fig. 2(a)]. $S_+^{\gamma0} \approx 53.5\%$ at $t_\gamma$. Therefore we include this effects in our simulations and the analytical calculation of positron polarization is shown in Fig. 3(a). The
where a with an acceleration gradient $G$ the Thomas-Bargmann-Michel-Telegdi equation [48–50] is also

(b) Average energy of captured positrons $\bar{E}$, (red-circles) and its linear profit (black-dashed) vs the interaction time $t$, respectively, with an acceleration gradient $G \approx 3.58$ GV/cm. (c) Energy spectra of captured positrons $dN_e/\bar{E}_e$ at the instant of finishing of pair creation $t_f = 40T_1$ (black-dashed) and at the end of the simulation $t_f = 1000T_1$ (black-solid) and $\bar{E}_e$ at $t_f$ (blue-solid) vs the positron energy $E_e$, respectively. (d) Normalized angular distributions of positrons at $t_i$ (black-dash-dotted) and $t_f$ (black-solid), and $\bar{E}_e$ at $t_f$ (blue-solid) vs the transverse angular divergence of the positrons $\theta_i = \arctan(p_{z,i}/p_{r,i})$, respectively. Initial parameters of the laser pulse, electron beams and plasma are given in the text.

polarization degree is inversely proportional to the positron energy, which affects the final polarization distribution of the accelerated positrons [see Fig. 2(c)]. Since in our case the QED parameter of the positron $\chi_s \propto a_{\text{wake}}\gamma_s[1 - \cos(\theta_L)] \ll 1$ [see Fig. 3(b)], the radiative depolarization effect is very weak, where $a_{\text{wake}}$ represents the invariant field parameter and $\gamma_s$ the Lorentz factor of positron. The depolarization effect derived from the spin procession in the wakefield govern by the Thomas-Bargmann-Michel-Telegdi equation [48,50] is also quite weak [51,52]. Consequently, the final positron polarization distribution mainly depends on the initial pair creation process and the conditions for the positron selection during the trapping and continuous acceleration processes. The last two processes rely on the wakefield structure. The positrons inherit transverse momenta $p_{z,i}$ from the seed electrons via intermediate $\gamma$ photons. During acceleration, the positrons with large-$p_{z,i}$ may escape from the central focusing region and are then expelled out of the bubble by the outer defocusing transverse field. The positrons with low-$p_{z,i}$ can be continuously trapped in the acceleration phase [see Figs. 3(c)-(f)]. Finally at $t_f = 1000T_1$ about 74.12% positrons are accelerated with an average energy increase of about 350 MeV in a distance $\leq 1$ mm, reaching $\bar{E}_e \approx 1.24$ GeV [see Fig. 2(b)], and the acceleration gradient is $G \approx 3.53$ GV/cm [see Figs. 3(g) and (h)]. The final average positron polarization is $\bar{E}_e \approx 31.77\%$, which is only slightly depolarized after acceleration [see Fig. 2(a)]. In the period of $200T_1 \leq t \leq 1000T_1$ some high-energy positrons with low polarization gradually escape from the focusing region [see Fig. 3(i)], therefore, the polarization increases a little. At $t_f$ the positron polarization distribution around the peak area of the energy spectrum within the FWHM declines approximately from 70% to 15%. Such distribution provides a possible

\[ N_+^{\text{cap}}(t) \approx \epsilon_x + \chi_x, \]
a way to further increase the polarization by the energy-selection technique\cite{53}.

Besides the trapping ratio and polarization degree, the energy spread and divergence are also important factors for future applications. In Fig. 2(c), we find that the relative energy spread of the positrons decreases by about 26% after the wake acceleration compared to the instant of the pair creation \(t_i\). While, the absolute energy spread does not increase during the acceleration, because the seed beam not only ‘provides’ the pairs but also flattens the local acceleration field [see Figs. 3(g)-(j)] ensuring uniform acceleration and avoiding energy dispersion. The angular divergence of the positron beam is also improved by the focusing field to \(\Delta \theta_i \approx 20\) mrad, which is about 50% lower than that at \(t_i\) [see Fig. 2(d)], the polarization is nearly uniform (\(S_+ \approx 32.67\%\)) within the FWHM labelled by the two dashed purple lines). One can see that there is an asymmetric angular distribution at \(t_f\) in Fig. 2(d). This is induced by the unbalanced plasma perturbations [indicated in Figs. 3(d) and (f)], originating from the laser incidence from one side.

Finally, we study the impact of the initial parameters on the trapping, acceleration and polarization of the positrons in Fig. 4. As the collision angle \(\theta_{ti}\) increases from 95° to 125° [see the interaction scenario in Fig. 1], the probabilities of photon emission and pair production (determined by \(\chi_e \propto a_0\gamma e[1-\cos(\theta_{ti})]\) and \(\chi_p \propto a_0\gamma_p[1-\cos(\theta_{ti})]\), respectively) are both enhanced, thus, \(N_{\text{cap}}^+\) increases. At the same time the average energy decreases due to \(\varepsilon_+ \propto \sum e_i/N_{\text{cap}}^+ \propto \sum e_i,0/N_{\text{cap}}^+.\) 

In conclusion, utilizing both advantages of laser-driven QED process and plasma wakefield acceleration we have proposed a compact scheme for positron polarization, trapping and acceleration. Dense GeV positron beams with a spin polarization up to 70% and improved beam quality compared with the scheme of single laser-electron collision can be achieved. By using multi-staged wakefield acceleration with currently achievable laser facilities, this scheme also provides a possible way to generate highly-polarized positron beams with hundreds of GeVs energy for future compact research and application platforms of high-energy and particle physics.

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