Positron beam acceleration driven by laser-accelerated electron beam

Zhangli Xu,1,2 Baifei Shen,1,3,* Jiancai Xu,1† Tongjun Xu,1 Lingang Zhang,1 Shun Li,1 Liangliang Ji1,4, and Zhizhan Xu1

1 State Key Laboratory of High Field Laser Physics, Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201800, People’s Republic of China
2 Center of Materials Science and Optoelectronics Engineering, University of Chinese Academy of Sciences, Beijing 100049, People’s Republic of China
3 Department of Physics, Shanghai Normal University, Shanghai, 200234, China
4 Center for Excellence in Ultra-intense Laser Science, Chinese Academy of Sciences, Shanghai 201800, China

A positron beam, produced in copper target based on laser-accelerated energetic electrons, is accelerated from a few MeVs to several hundred MeVs in strong longitudinal electric field induced by the co-propagating high-density electron beam. This new acceleration scheme for positron beams is demonstrated by two-dimensional particle-in-cell simulation and Monte-Carlo code. The electron beam after passing through the copper target keeps its high density ~10\(^{17}\) cm\(^{-3}\) for 0.7 m propagation distance, with the guiding from an external longitudinal magnetic field of 30 T and provides a strong acceleration field of GV/m for the positrons. Simulation results indicate that a positron beam with an initial Maxwellian-energy-spectrum of \(T_p = 24.1\) MeV is accelerated to quasi-monoenergetic peaks up to 796.5 MeV with energy spread of 18.7% when 10 PW laser pulse is employed. The angular divergence of the positron beam is 2.3 mrad and the charge is 12 pC. This proposed method resolves the creation, injection and acceleration of positrons in a single set-up, which offers a new way to accelerate high-energy positrons for potential modest-sized all-optical electron-positron colliders.

Particle collision is an important approach to study the most fundamental pieces of our universe and to answer questions such as what is dark matter made of, and
what breaks the mechanism of electroweak symmetry [1]. Discovering the Higgs boson at the Large Hadron Collider (LHC) in the European Organization for Nuclear Research (CERN) is one of the most remarkable achievements obtained by particle collisions [2]. Electron-positron collisions, whose events are much cleaner than proton-proton collisions because there are only elementary particles involved, are being widely considered based on big machines, such as International Linear Collider (ILC) [3] and Compact Linear Collider (CLIC) [4]. However, the acceleration gradient of these conventional accelerators is limited to ~100 MV/m mainly because of material damage threshold, and the acceleration distance reaches a few tens of kilometers in order to realize energy frontier up to TeV-class [4], which generates enormous expense. Thus, it is essential to look for other acceleration mechanisms to accelerate electrons and positrons. In the past forty years, electron acceleration driven by femtosecond relativistic laser pulse has made remarkable progress since the concept of laser wakefield acceleration (LWFA) being first proposed [5]. The electron energy has reached 4 GeV [6] and even 7.8 GeV with small energy spread reported recently[7]. Nowadays, the electron beam with short pulse duration of a few femtoseconds [8], small angular divergence of less than 1.5 mrad [9] and beam charge up to 10 nC [10] can be readily obtained. These high-quality laser-driven electrons have been successfully used to generate Maxwellian-energy-spectrum positron beam with maximum energies up to hundreds MeVs [11-14] at sufficiently low emittance[15].

Realization of electron-positron collisions requires mono-energetic GeV-class or even TeV-class positrons. Besides the expensive conventional acceleration method, several new methods have been proposed to accelerate positrons in plasma, such as particle driven wakefield acceleration (PWFA) [16], laser driven sheath field acceleration [17, 18] and LWFA [19]. In order to overcome the problem of transverse defocusing of positrons in the wakefield driven by electrons [20], plasma channel [21], hollow electron beam [22] and two electron driven beams [23] have been applied. Donut shaped wakefield driven by Laguerre-Gaussian (LG) laser pulses also helps to avoid the defocusing of positron beam. [24] Despite the impressive beam
quality that is able to be achieved by these methods, positron acceleration is still challenging and has been less studied experimentally due to the lack of suitable driving beams and positron sources [25-27]. Therefore, finding a practical approach to generate and accelerate positrons to higher energy is still an open research area.

In this letter, we propose a novel scheme to create positron source and further accelerate it to GeVs in vacuum, driven directly by the laser-accelerated electron beam, as shown in FIG. 1. The scheme is composed of three stages, stage I is the generation of high-charge high-energy electrons in LWFA. Stage II is the positron generation in copper targets via the routine Bethe-Heitler (BH) process [28] and stage III is the acceleration process for positrons. In stage III, the energetic electron beam drives the intense longitudinal electric field to accelerate the co-propagating positrons. Our combined simulations (EPOCH-Geant4-EPOCH) confirm that an quasi-monoenergetic position beam peaking at 796.5 MeV with 18.7% energy spread, 2.3 mrad angular divergence, 12 pC beam charge and 6.4 fs pulse duration can be obtained by a $1.37 \times 10^{20} \text{W/cm}^2$, 223 J driving laser pulse, while the initially generated positrons are of a Maxwellian energy spectrum with $T_p = 24.1$ MeV. The laser-driven electron beam provides an acceleration gradient of several GV/m, which is between the conventional accelerators ($\sim 100$ MV/m) [3, 4] and PWFA ($\sim 100$ GV/m). But the set-up is far less demanding than conventional accelerators and does not require special injection designs or high-quality positron sources as in PWFA. Therefore, the proposed method is a promising candidate for high-energy positron sources in the future to develop modest-sized all-optical electron-positron colliders.
FIG. 1. (a) Schematic of positron acceleration in vacuum driven by laser-accelerated electron beam. The scale of the diagram is not the actual scales. (b) Electron energy spectrum after stage I. (c) The energy spectrum of positrons after stage II (black dotted line) and stage III (red solid line).

The acceleration process of high-charge energetic electron bunch, favorable for accelerating positrons, has been studied by two dimensional (2D) particle-in-cell (PIC) simulation code EPOCH [29]. The simulation window, moving at the light speed $c$, is of $L_x \times L_y = 180\lambda \times 360\lambda$ in size with $2000 \times 750$ cells. Each cell is filled with 10 macro particles. The circular-polarized laser pulse propagates along the $x$ direction from the left side with super-Gaussian spatial distribution and $\sin^2$ temporal profile. Its normalized vector potential, central wavelength, focal spot diameter and duration are $a_0 = eA/m_e c^2 = 8/\sqrt{2}$, $\lambda = 0.8 \mu m$, $r_0 = 60\lambda$ and $\tau = 45$ fs respectively,
where $A$ is the vector potential, $e$ and $m_e$ are the electron charge and mass respectively. The plasma density along the laser propagation direction first increases sinusoidal from 0 to $3 \times 10^{18} \text{cm}^{-3}$ within a distance of $290 \lambda$, decreases sinusoidal to $2 \times 10^{18} \text{cm}^{-3}$ after a short transition length of $10 \lambda$ and maintains the density of $2 \times 10^{18} \text{cm}^{-3}$ afterwards till 15 mm. The intense laser pulse excites plasma wakefield in the plasma. Electrons are continuously injected into the plasma wave when the laser passes through the density transition region and further accelerated to high energies. The charge of this electron beam at energies above 5 MeV and within a divergence angle of $1.5^\circ$ reaches 3 nC when it comes out of the plasma. These electrons have a continuous energy spectrum with cutoff energy of 2 GeV, as shown in FIG. 1. (b). The transverse size of the electron beam is 15.5 $\mu$m (FWHM) and the longitudinal length is 4.5 $\mu$m (FWHM).

This high-charge energetic electron beam impinges onto a 1 mm-thick copper target, and triggers the generation of high-energy Gamma photons via bremsstrahlung [30] and further the production of electron-positron pairs via the BH process. Numerical simulations performed by the Monte-Carlo code Geant4 [31] are able to account for the positron generation process and provide the energy and angular spectrum of both electrons and positrons after they exit the copper target. Electrons generated from stage I are sampled at $5.34 \times 10^{-4}$ ratio by reserving the energy and angular spectrum, and input into the copper target in the Monte-Carlo simulations. The copper target with thickness of 1 mm is set 0.5 mm away from the gas target. For the sampled $10^7$ electrons, we obtain $5.03 \times 10^4$ positrons, roughly two orders of magnitudes lower than that of electrons. They have a Maxwellian-energy-spectrum of $T_p = 24.1 \text{ MeV}$ and cutoff energy 1.7 GeV, as shown by the black dotted line in FIG. 1. (c). The positron beam has small divergence angle of 49.4 mrad (FWHM). After the cooper target, the electron beam still contain 93.4% of its initial energy. It is elongated slightly both in transverse and longitudinal dimensions. The transverse size of electron beam is 44.8 $\mu$m (FWHM) and longitudinal length is 5.3 $\mu$m (FWHM). The positron beam is in similar size as compared to the electron beam (5.3 um and 42.5um
in longitudinal and transverse dimensions), containing 12.1 pC beam charge according to the number ratio. Both electron and positron beams, leaving the copper target, co-propagate forward and overlap in space. Necessarily, the annihilation of positrons and electrons is negligible during the co-propagating process since they propagates with low density in the same direction. The lifetime of a positron is expressed as $\tau = 1/(\pi r_0^2 n_e)$, where $r_0$ is electron classical radius, $n_e$ is the electron density where positrons located. In our case, positrons are able to propagate several kilometers without apparent annihilation.

After the copper target, the electron beam still keeps its relative-high density and thus drives a strong longitudinal positive electric field to accelerate positrons. The acceleration process is verified by 2D PIC simulation code EPOCH. Simulations use a moving window with sizes of 80 µm×800 µm divided into 200×1200 cells with ten macro particles per cell for electrons and positrons. A hybrid beam constituted by electrons and positrons is initialized at the left side of simulation box. The driving electron beam contains the charge of 3 nC and has a density profile $n_e = n_{e0} \exp\left(-x^2/\delta_{ex}^2 - y^2/\delta_{ey}^2\right)$, where $n_{e0} = 1.46 \times 10^{18}$ cm$^{-3}$ is the peak electron density, $\delta_{ex} = 3.18$ µm ($\delta_{FWHM} = 5.3$ µm) and $\delta_{ey} = 26.9$ µm ($\delta_{FWHM} = 44.8$ µm) are electron beam length in $x$ and $y$ direction respectively, consistent with the size of electron beam in stage II. The induced current by this electron beam is estimated as 159 kA, well below the Alfvén current limit. The 12.1 pC positron beam takes the same density profile as the electron beam, but with $n_{p0} = 6.5 \times 10^{15}$ cm$^{-3}$, $\delta_{px} = 3.18$ µm ($\delta_{FWHM} = 5.3$ µm) and $\delta_{py} = 25.5$ µm ($\delta_{FWHM} = 42.5$ µm) respectively. Positrons have an initial Maxwellian energy distribution at temperature $T_p = 24.1$ MeV. These parameters are also taken from stage II. We apply an external longitudinal magnetic field of $B_x = 30$ T to maintain the electron beam size hence the high charge density during long distance propagation. It also efficiently focuses the 49.4 mrad (FWHM) positrons when ejected from copper target.

Our PIC simulation confirms that the electron beam induces strong longitudinal
electric field in vacuum to accelerate the co-propagating positron beam efficiently. The position beam with charge of about 12 pC is able to be accelerated to peak at 796.5 MeV with 18.7% energy spread after a distance of 0.7 m, as shown in FIG. 1(c). The longitudinal length of positron beam decreases from 5.3 μm to 1.9 μm (FWHM), correspondingly the pulse duration of 6.4 fs. FIG. 2(b) plots the density evolution of positron beam in this acceleration process and indicates that the positron beam keeps its high density as \( \sim 2 \times 10^{15} \text{ cm}^{-3} \) and its transverse size increases at most beginning because of large angular divergence and then slightly decreases to 187.3 μm at 0.7 m. For a 2.3 mrad (FWHM) angular divergence, the emittance of positron beam is as small as 0.05 mm mrad (r.m.s).

\[
\begin{align*}
\text{FIG. 2.} \quad & \text{The density of positrons at } x \sim 140, 420, \text{ and } 700 \text{mm.}
\end{align*}
\]

The positron beam gains high energy from the co-propagating electron beam through strong longitudinal field. Moreover, it keeps small size and high density during the acceleration process. The transverse focusing field for positrons induced by the electron beam is estimated by \( E_y = \beta_e c B_z \), where \( E_y \) is the transverse electric field, \( \beta_e = (1 - 1/\gamma_e^2)^{1/2} \) is the normalized electron velocity and \( B_z \) is the magnetic field in \( z \) direction, respectively. It has a peak value of 10 GV/m and is radially inward in the region where the majority of the positron beam locates, as shown in FIG. 3(a). Here, positrons are represented by dark green dashed ellipse in FIG. 3(a) and FIG. 3(b). These positrons are focused in the strong transverse field and at the same time
experiencing the intense longitudinal accelerating field $E_x$ of several GV/m. The lineout of $E_x$ at $x = 0.64$ mm, plotted in FIG. 3(b), shows that the maximum acceleration field reaches above 40 GV/m, which is 2 orders of magnitudes higher than that in conventional accelerators. The density of the driving electron beam will decrease with propagation distance because of the angular divergence, energy loss and coulomb explosion. But due to the longitudinal magnetic field $B_x = 30$ T, the density can remain at a relatively high level. For instance, the acceleration field $E_x$ is at 1 GV/m after propagating for 0.7 m. Moreover, the acceleration field $E_x$, plotted in Fig. 3(d), decreases with $x$ when $x > x_0$ ($x_0$ is the place where $E_x$ has maximum value). Most of positrons locate at the positions $x > x_0$. The positron beam has an energy chirp, i.e., with more energetic positrons in the beam head and less ones in the tail. In such an acceleration field, positrons with initial lower energies fall behind and experience higher acceleration field and gain more acceleration than those with higher initial energies. Therefore the energy chirp is eliminated, leading to a narrow energy spread width as the acceleration goes on.

The longitudinal and transverse electric fields induced by the driving electron beam could be well described by Poisson equation in the rest frame of the energetic beam $O'x'y'z'$ ($S'$). Here $O$-xyz ($S$) refers to the laboratory frame. In the co-moving frame $S'$, the electron density is expressed as $n_e' = n_{e0}' \exp\left(-\frac{x^2}{\delta^2_x} - \frac{y^2}{\delta^2_y}\right)$, where $\delta_x' = \gamma \delta_x$, $\delta_y' = \delta_y$, and $\gamma$ is the Lorentz factor. $n_{e0}'$ is calculated by the conservation of particle number $\int n_e' dx dy = N$, where $N$ is the total number of electrons in $S$ frame, which is set to be the same as that in simulations. Thus, the potential generated by electrons is described by Poisson equation

$$\nabla^2 \phi' = -\frac{n_e'}{\varepsilon_0},$$

where $\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}$ is the Laplace operator. Here we neglect the
contribution of positrons to the field since the initial positrons density is lower than the electrons density by two orders of magnitude. The electric field then can be obtained by $\mathbf{E} = -\nabla \phi$. As we have obtained longitudinal electric field $E_x'$ and transverse electric field $E_y'$ in co-moving frame $S'$, we calculate electric field $E_x$ and $E_y$ in laboratory frame $S$ by Lorentz transformation as

$$
E_x = E_x',
E_y = \gamma (E_y' + \beta_z B_z').
$$

According to Eq. (2), we plot theoretical results of the transverse electric field $E_y$ (red dash line) in FIG. 3(c), which matches the lineout of $E_y$ from the simulations at $x = 0.6425$ mm very well. This strong transverse field efficiently focuses the positron beam and thus the beam divergence greatly decreased. The on-axis longitudinal field at $x \sim 0.64$ mm reaches a few tens GV/m [black solid line in FIG. 2(d)].
FIG. 3. Transverse field $E_y$ (a) and longitudinal field $E_x$ (b) induced by driving electron beam when it propagates at $x \sim 0.64$ mm. Here, the profile of positron beam is represented by the dark green dashed ellipse. The lineout of both $E_y$ and $E_x$ is plot in (c) and (d) and the $E_y$ lineout from analytical theory is given as dashed red line at $x \sim 0.6425$ mm (c). The density distribution of driving electron beam is also plotted.

Simulation results show that almost all positrons generated in the copper target catch up with the acceleration field induced by the energetic electron beam. In order to study the trapping condition and the acceleration process of positrons in stage III, we adopt a one-dimensional analysis according to the normalized Hamiltonian approach [32-34]. When the positrons velocity is equal to the electrons velocity, the positrons are trapped into the acceleration field and further accelerated. The motion of one positron is given by

$$h(\xi, p_x) = \sqrt{1 + p_x^2 - \beta_e p_x + \rho_e \phi(\xi)} = h_0,$$

where $\phi(\xi)$ is the normalized scalar potential of longitudinal field with $\xi = x - ct$. $\rho_e = m_e / m_\gamma = 1$ is the mass ratio of electron and positron. The integral constant $h_0$ depends on the initial velocity of the positron $h_0 = \sqrt{1 + p_0^2 - \beta_e p_0}$, $p_0 = p_x(\xi_0) = \gamma \beta_e p_0$ is the initial momentum of the positron, where $\beta_e p_0$ is the initial normalized positron velocity. Thus the longitudinal momentum of the positron $p_x$ is
given by
\[ p_x = \frac{\beta_c h_0 - \rho_0 \phi(\xi)}{1 - \beta_c^2} \pm \frac{\sqrt{[h_0 - \rho_0 \phi(\xi)]^2 - (1 - \beta_c^2)^2}}{1 - \beta_c^2}, \]  
(4)
where “+” stands for \( \xi \) increasing with time and “-” stands for \( \xi \) decreasing with time.

To exemplify the general property of the system with Hamiltonian \( h(\xi, p_x) = h_0 \), we show its phase portrait \( p_x(\xi) \) in Fig. 4, which represents the motion of the positrons whose initial kinetic energy at \( \xi = \xi_0 \) is \( E(\xi_0) = \sqrt{1 + p_0^2} - 1 \). Here, the kinetic energy is defined as \( E(\xi) = \sqrt{1 + p_x^2} - 1 \). Along its path from \( \xi_0 \) to \( \xi \), the positron gains the following kinetic energy
\[ \Delta E = E(\xi) - E(\xi_0) = \gamma_0^2 (-\rho_0 \Delta \phi + \beta_0^2 \chi_0 + \beta_0 \sqrt{(-\rho_0 \Delta \phi + \chi_0)^2 - 1/\gamma_0^2}) - \beta_0 p_0, \]  
(5)
where \( \Delta \phi = \phi(\xi) - \phi(\xi_0) \), \( \chi_0 = \sqrt{1 + p_0^2} - \beta_0 p_0 \), and \( \gamma_0 = 1/\sqrt{1 - \beta_0^2} \).

In our theoretical model, \( \phi(\xi) \) is calculated from the acceleration field \( E_x \) taken from PIC simulation above. Since \( E_x \) slowly decreases during the acceleration process, here we choose \( E_x \) at \( x = 5 \) mm as an average constant field for the theoretical analysis, which is shown by the purple dash-dot line in FIG. 4. The phase portrait of the Hamiltonian system with the Hamiltonian \( h(\xi, p_x) \) has a threshold value of momentum \( p_{th} \), which ensures the positrons exactly being trapped into the electric field. The critical trapping condition is that the velocities of positrons are equal to the electrons and the electric potential reaches the maximal value \( \phi_{max} \), i.e., the momentum of positrons are \( p_{th} = \beta_c / \sqrt{1 - \beta_c^2} \) and \( \phi_{th} = \phi_{max} \). Thus, the initial integral constant \( h_0 \) of positrons being critical trapped satisfy \( h_0 = \sqrt{1 + p_{th}^2} - \beta_0 p_{th} + \phi_{max} \), and its energy reaches the maximal value \( E_{max} = \gamma_c^2 (1 + \beta_c) \phi_{max} \) at the top of the trajectories, represented by the pink solid line in FIG. 4. In our case, the critical
trapped energy is 0.67 MeV. Positrons with energies lower than 0.67 MeV can not be trapped and fall behind the electric field, represented by red dash line in FIG. 4. The positrons with initial energy above 0.67 MeV are trapped into the acceleration field and further accelerated to higher energy. The initial temperature of positrons in our simulation is $T_p = 24.1$ MeV. A majority of them are much higher than critical energy. Therefore most of them easily get trapped into the acceleration field and gain energy. The peak energy in typical simulation at 0.7 m is 796.5 MeV and the cutoff energy is 2.5 GeV, which is lower than theoretical results (9.2 GeV, black solid line in FIG. 4.). Because the theoretical line describes the whole positron acceleration process including the dephasing part and the positrons will overtake the electric field, while the positrons at 0.7 m in the PIC simulation are far away from reaching the maximum energy gain in this acceleration scheme. Moreover, the pulse duration of driving electron beam elongates due to the energy loss. Its density will reduce because of initial divergence and Coulomb expansion and thus the amplitude of acceleration field decreases during propagation. Therefore positron beam will be further accelerated to even higher energy if stronger external magnetic field is applied. Figure 4 also shows that positrons with lower initial energy and can be captured by the electric field experience a longer relative displacement and thus, they will get more energy gain than those with higher initial energies, which can be calculated by Eq. (5).
FIG. 4. Trajectories of positrons with different initial energies in the electric field. The purple dash-dotted line shows the electric field $E_x$ at 5 mm obtained from PIC simulations. The pink solid line shows the critical trapping trajectories, and the blue, black and red solid lines show trajectories of positrons with energy of 5 MeV, 24.1 MeV and 240 MeV, respectively. Positrons cannot be trapped is represented by red dash line.

The electron beam produced in the laser plasma accelerator has much higher density than that in conventional accelerator. Therefore it provides strong longitudinal electric field for co-propagating positrons after copper target since the longitudinal electric field $E_x$ is linearly proportional to electrons density $E_x \propto n_e$. We have studied the energy gain of positrons dependence on the density of driving electron beam. Series of simulations have been performed to scan the electron beam density with fixed other electron/positron beam parameters. Here the driving electron beam has initial energy of 1 GeV and zero angular divergence. Positron beam has fixed energy of 24.1 MeV and zero angular divergence. We have found that the positrons can not be trapped by the electric-field induced by the driving electron beam whose density is lower than $0.9 \times 10^6$ cm$^{-3}$, represented by Gray area in FIG. 5. The fitting maximum energy line from the simulations is described as
\[ E_{e_{\text{max}}} = 0.85 \exp(0.018 n_e) - 1.01 \exp(-0.18 n_e) \]. Here, the units of \( E_{e_{\text{max}}} \) and \( n_e \) is GeV and \( 10^{16} \text{cm}^{-3} \), respectively. The fitting curve indicates that the maximum energy of positrons \( E_{e_{\text{max}}} \) at 0.7 m increases rapidly with the density of driving electron beam and tend to be saturated when the electrons density reaches further higher. Because the electron beam has such high initial density that the Coulomb expansion plays a significant role and thus the electron beam expands rapidly, which is no longer able to provide strong acceleration field. Thus, it is necessary to apply an appropriate longitudinal magnetic field externally to keep electrons from spreading transversely.

FIG. 5. The scaling relation of maximum energy of positrons at \( x \sim 0.7 \text{ m} \) with the density of driving electron beam.

In conclusion, we presented a simple novel scheme for GeV-level positron acceleration based on laser-accelerated high-density electron beam. The positrons created from routine BH process in copper target get high-energy gain from longitudinal electric field induced by co-propagating electrons after the copper target. Series of simulations (EPOCH-Geant4-EPOCH) confirmed that positrons with an
initial Maxwellian energy distribution with temperature of $T_p = 24.1$ MeV are able to be accelerated to 796.5 MeV with an energy spread of 18.7% and a small angular divergence of 2.3 mrad (FWHM). This acceleration method is able to provide high-energy positron beam with narrow energy spread and offers a new concept towards modest-sized all-optical electron-positron colliders.

This work was supported by Ministry of Science and Technology of the People’s Republic of China (2018YFA0404803 and 2016YFA0401102), Strategic Priority Research Program of the Chinese Academy of Sciences (XDB16) and the Scientific Equipment Research Project of Chinese Academy of Sciences (Project No. 1701521X00).

*bfshen@mail.shcnc.ac.cn
†jcxu@siom.ac.cn

[1] T. Hambye and M. H. G. Tytgat, Physics Letters B 659, 651 (2008).
[2] G. Aad et al., Physics Letters B 716, 1 (2012).
[3] F. Keisuke, G. christophe, P. Michael E, B. Tim, Y. Gao, K. Shinya, and K. Hyungdo, arXiv:1506.05992.
[4] M. Aicheler, P. Burrows, M. Draper, T. Garvey, and P. Lebrun, A multi-TeV linear collider based on CLIC technology: CLIC conceptual design report, 2012.
[5] T. Tajima and J. M. Dawson, Physical Review Letters 43, 267 (1979).
[6] W. P. Leemans et al., Phys Rev Lett 113, 245002 (2014).
[7] A. J. Gonsalves et al., Physical Review Letters 122, 084801 (2019).
[8] J. Osterhoff et al., Phys Rev Lett 101, 085002 (2008).
[9] T. Xu et al., Physics of Plasmas 23, 033109 (2016).
[10] S. Li et al., Physics of Plasmas 24, 093104 (2017).
[11] G. Sarri et al., Nat Commun 6, 6747 (2015).
[12] G. Sarri et al., Phys Rev Lett 110, 255002 (2013).
[13] G. Sarri et al., Plasma Physics and Controlled Fusion 55, 124017 (2013).
[14] A. Alejo, R. Walczak, and G. Sarri, Sci Rep 9, 5279 (2019).
[15] S. Lee, T. Katsouleas, R. G. Hemker, E. S. Dodd, and W. B. Mori, Phys Rev E Stat Nonlin Soft Matter Phys 64, 045501 (2001).
[16] Y. Yan, Y. Wu, J. Chen, M. Yu, K. Dong, and Y. Gu, Plasma Physics and Controlled Fusion 59,
045015 (2017).
[18] H. Chen et al., Phys Rev Lett 105, 015003 (2010).
[19] E. Esarey, C. B. Schroeder, and W. P. Leemans, Reviews of Modern Physics 81, 1229 (2009).
[20] K. V. Lotov, Physics of Plasmas 14, 023101 (2007).
[21] L. Yi et al., Sci Rep 4, 4171 (2014).
[22] N. Jain, T. M. Antonsen, Jr., and J. P. Palastro, Phys Rev Lett 115, 195001 (2015).
[23] X. Wang, R. Ischebeck, P. Muggli, T. Katsouleas, C. Joshi, W. B. Mori, and M. J. Hogan, Phys Rev Lett 101, 124801 (2008).
[24] J. Vieira and J. T. Mendonça, Physical Review Letters 112, 215001 (2014).
[25] S. Corde et al., Nature 524, 442 (2015).
[26] B. E. Blue et al., Phys Rev Lett 90, 214801 (2003).
[27] A. Doche et al., Sci Rep 7, 14180 (2017).
[28] H. Bethe, Heitler, W Proc. R. Soc. Lond. A 146, 83 (1934).
[29] T. D. Arber et al., Plasma Physics and Controlled Fusion 57, 113001 (2015).
[30] H. W. Koch and J. W. Motz, Reviews of Modern Physics 31, 920 (1959).
[31] E. Liang et al., Sci Rep 5, 13968 (2015).
[32] T. J. Xu et al., Physics of Plasmas 22, 073101 (2015).
[33] S. V. Bulanov et al., Plasma Physics Reports 32, 263 (2006).
[34] B. F. Shen, Physics of Plasmas 14, 053115 (2007).