Laser wakefield and direct acceleration with ionization injection

Xi Zhang\textsuperscript{1}, Vladimir N Khudik\textsuperscript{1}, Alexander Pukhov\textsuperscript{2} and Gennady Shvets\textsuperscript{1}

\textsuperscript{1} Department of Physics and Institute for Fusion Studies, The University of Texas at Austin, Austin, TX 78712, USA
\textsuperscript{2} Institut für Theoretische Physik I, Universität Düsseldorf, Düsseldorf 40225, Germany

E-mail: gena@physics.utexas.edu

Received 30 September 2015, revised 4 December 2015
Accepted for publication 22 December 2015
Published 9 February 2016

Abstract
We demonstrate using particle-in-cell simulations that electrons can be injected into a hybrid laser wakefield and direct laser accelerator via ionization injection. We propose an accelerator and injector scenario that utilizes two laser pulses. The first (pump) pulse produces the plasma ‘bubble’ by expelling the plasma electrons generated by its leading edge from the low-Z component of the gas mixture, and then injects electrons into the bubble by ionizing the high-Z component. The second time-delayed laser pulse resonantly interacts with these injected electrons undergoing betatron oscillations inside the bubble. We show that the electrons ionized off-axis and on-axis but off the peak ionization phase possess sufficient transverse energy to undergo efficient direct laser acceleration (DLA). When combined with their acceleration by the bubble’s longitudinal plasma wake, DLA can double the total energy gain and produce a monoenergetic beam.

Keywords: ionization injection, laser wakefield acceleration, direct laser acceleration, plasma bubble regime

(Some figures may appear in colour only in the online journal)

1. Introduction

The development of laser-plasma accelerators \cite{1} has been driven by the combination of the rapid advances in laser technology and the introduction of novel ideas that enabled higher quality, higher energy electron beams \cite{2–4}. An example of one such idea in the area of laser-wakefield acceleration (LWFA) is the full plasma electron blow-out regime \cite{5, 6}, where an ultra-short laser pulse creates a relativistically moving plasma ‘bubble’ capable of trapping and accelerating plasma electrons to ultra-high energies. GeV-scale mono-energetic electron beams have been recently obtained \cite{7–10} in the bubble regime. As LWFA matures, new acceleration mechanisms are being explored to further increase the electron energy gain and to broaden the scope of applications beyond high-energy physics, e.g. to novel compact radiation sources.

One such acceleration mechanism, proposed almost two decades ago \cite{11, 12} but currently experiencing considerable renewed interest in the context of the electron acceleration in the bubble regime \cite{13–20}, is the direct laser acceleration (DLA). Unlike LWFA, DLA is a plasma-based acceleration mechanism that relies on the transverse component of laser’s electromagnetic field to accelerate electrons. Resonant electron acceleration by the laser field takes place when the Doppler-shifted laser frequency $\langle \omega_d \rangle \equiv \omega_L (1 - \langle v_x \rangle / \gamma_{ph})$ matches the $l$th harmonic of the electron’s betatron frequency $\omega_l = \omega_p \sqrt{2} \langle \gamma^{-1/2} \rangle$. Here $\langle v_x \rangle$ and $\langle \gamma^{-1/2} \rangle$ are the time-averaged over a betatron period longitudinal velocity and inverse square root relativistic factor of the accelerated electron, $\omega_L$ and $\gamma_{ph}$ are the frequency and phase velocity of the laser field, and $\omega_p = \sqrt{4\pi n e^2 m}$ is the electron plasma frequency, and $l = 1, 3, 5 \ldots$ is an odd number that corresponds to higher-order resonance for $l > 1$ \cite{21, 22}.

A key requirement for effective DLA is that the initial energy $\epsilon_\perp$ of betatron motion of an injected plasma electron be sufficiently high to overcome its rapid reduction due to electron acceleration by the longitudinal field of the plasma bubble \cite{20}.
Therefore, it is important to devise an appropriate injection scheme that satisfies this requirement. In general, electron injection in all plasma-based electron accelerators can be classified into density-based and laser-based. Density-based approaches involve shaping the longitudinal plasma density profile at the entrance of the as a single or multiple density ramps [20, 23–27]. A bump-shaped density profile has been suggested as a possible approach to injecting into a hybrid laser wakefield/direct laser accelerator [20].

Laser-based injection mechanisms do not require any plasma density engineering, and are generally considered to be experimentally simpler. Those include ionization of a high-Z gas [28–30], colliding multiple laser pulses [31, 32], and engineering rapid laser pulse evolution to produce a time-varying plasma bubble [9, 33–36]. Ionization injection is considered particularly straightforward because of its relative controllable and stable features. It has been demonstrated in multiple experiments [29, 37–39], and was theoretically shown to be promising for producing low-emittance beams [40, 41]. Note also that particle injection into the bubble due to the plasma field was experimentally verified in [38]. Here, we demonstrate that ionization injection is also an excellent injection mechanism into a laser wakefield and direct accelerator (LWDA), thus making it an attractive alternative to the earlier proposed [20] density-based injection into a LWDA.

The remainder of the paper is organized as follows. In section 2 we review the basic requirements for efficient LWDA and illustrate them by carrying out test particle simulation. The results of self-consistent 2D particle-in-cell (PIC) simulations carried out using the VLPL code are presented in section 3. We then classify several representative electrons that are injected via laser ionization and experience the combined laser wakefield and direct laser acceleration. Conclusions and the directions for future research are outlined in section 5.

2. Single-particle simulations

The theoretically proposed concept of the combined LWFA and DLA of electrons inside a plasma bubble, referred to below as a LWDA, enables synergistic combination of the two acceleration mechanisms [20]: their separate energy gains combine while the wakefield acceleration is further increased by delayed dephasing which is caused by large-angle betatron motion of the DLA electrons. However, a LWDA relies on two conditions: (a) spatio-temporal overlap between injected electrons and the laser field, and (b) large initial transverse energy \( \epsilon_\perp = p^2_\perp/2m_e + m_e\omega_p^2 z^2/4 \) [16, 20, 42]. The first condition is rather intuitive; it can be satisfied by using the double-peaked laser pulse format schematically shown in figure 2. Delaying the second (DLA) with respect to the bubble-forming (pump) pulse ensures that the injected electrons overlap with the DLA pulse as soon as they reach the rear portion of the bubble.

The second requirement examined in [20] is less intuitive; we illustrate it in this section by describing the results of single-particle simulations that track an ensemble of electrons moving in the prescribed electromagnetic fields of the laser and bubble. For simplicity, we assume planar linearly polarized laser fields in the form of \( E_x^{(1)} = -E_0 \sin \omega_L(t - x/v_{ph}) \) and \( B_z^{(1)} = B_0 \sin \omega_L(t - x/v_{ph}) \), where \( B_0 = eE_0/v_{ph} \). The accelerating force and focusing forces inside the bubble produced by the combination of electric and magnetic fields are assumed in the form \( W_e = mc_0^2 \omega_p^2 (x - r_b - v_{ph}t)/2e \) and \( W_z = mc^2 \omega_p^2 z/v_{ph} \), respectively [42], where \( r_b \) and \( v_z \approx c(1 - 1/2\gamma^2) \) are the bubble’s radius and group velocity.

The resulting equations of motion are given by [13, 17, 18, 20]

\[
\begin{align*}
\frac{dp_x}{dr} &= -e \left( W_x - \frac{v_z}{c} B_y^{(1)} \right), \\
\frac{dp_y}{dr} &= -e \left( W_z + E_x^{(1)} + \frac{v_z}{c} B_y^{(1)} \right),
\end{align*}
\]

where the specific simulation parameters listed in the caption of figure 1 were chosen to be consistent with PIC simulations presented in section 3. In the DLA mechanism, the laser electric field \( E_x^{(0)} \) directly pumps energy into the transverse direction and the Lorentz force \( \vec{v} \times \vec{B} \)/c from the laser magnetic field re-distributes the energy to the longitudinal direction. Initially (at \( t = 0 \)) electrons are placed near the tail of the bubble and assigned a constant longitudinal momentum \( p_z = \gamma mc \) to ensure their co-propagation with the bubble. The transverse initial conditions \( (p_0, p_\perp) \) are chosen randomly inside the \( 0 < \epsilon_\perp \leq 2.3m_e^2 \) phase space ellipse as shown in figure 1(a). Note that the assumption of an infinitely long laser pulse in the model above implies that the accelerated electrons overlap with the laser field at all times. As more realistic PIC simulations presented in section 3 indicate the electrons slip ahead of the DLA pulse, which also undergoes energy depletion.

The color-coded electron energy gain \( A_e \) from the laser plotted in figure 1(a) as a function of the initial conditions demonstrates that a large value of \( \epsilon_\perp(t = 0) \) is a pre-condition for DLA [20]: only those electrons with large initial transverse energy gain considerable energy directly from laser. Qualitatively, this can be understood by noting that \( dA_e/dt \propto E_x^2 \hat{\beta}_\perp \gamma m_e \), where \( A_e \) is the energy gained directly from the laser field. Therefore, the acceleration rate due to DLA is small if the initial \( |\hat{\beta}_\perp| \) is small. The comparison of the \( A_e \)’s of two representative DLA (red) and non-DLA (blue) electrons with the corresponding initial transverse energies \( \epsilon_\perp^{\text{DLA}} = 1.8m_e^2 \) and \( \epsilon_\perp^{\text{non-DLA}} = 0.2m_e^2 \) is shown in figure 1(b). While the DLA electron gains \( A_e \approx 1100m_e^2 \) from the laser, the non-DLA electron does not gain any appreciable energy.

The monotonous growth of \( A_e \) for the DLA electron shown in figure 1(b) indicates that the resonance is maintained between the laser field and the electron’s betatron motion. To verify this conjecture, we plot the \( (\omega_L) \) and \( \omega_\perp \) in figures 1(c) and (d) for the DLA and non-DLA electrons, respectively. Clearly, the resonance condition \( (\omega_L) \approx \omega_\perp \) is preserved for the DLA electron, but is quickly violated for the non-DLA electron. Note that no averaging is needed for the \( \gamma^{-1} \) in the expression for \( \omega_\perp \). The reason for this is that both electrons, however, gain considerable energy \( A_W \) directly from the wake: \( A_W^{\text{DLA}} \approx 1200m_e^2 \).
and $A_{\text{DLA}} \approx 800mc^2$ at $x = 4$ mm. This steady energy gain washes out the high-frequency fluctuations in $\gamma$ due to DLA.

To interpret the results presented in figures 1(c) and (d), it is instructive to examine the ultra-relativistic limits of $\omega_d$ and $\omega_\beta$:

$$\langle \omega_d \rangle \approx \omega_L \left( 1 + \frac{\left(p_z^2/mc^2\right)^2}{2\gamma^2} + \frac{1}{2\gamma_{\text{ph}}} \right), \quad \omega_{\beta} \approx \frac{\gamma_{\text{ph}}}{\sqrt{2}\gamma},$$  

where we have introduced $\gamma_{\text{ph}} = 1/\sqrt{\psi_{\text{ph}} - 1}$. According to equation (2), the dependence of $\langle \omega_d \rangle$ on $\gamma$ is much stronger that of $\omega_{\beta}$ provided that $\gamma_{\text{ph}}$ is very large. Therefore, the $\langle \omega_d \rangle < \omega_{\beta}$ condition is rapidly reached for the non-DLA electron as the electron’s $\gamma$ rapidly increases due to wakefield acceleration. The situation is drastically different for the DLA electron because of the rapid increase of $p_z$ due to the laser field. Therefore, $\langle \omega_d \rangle$ decreases much slower for the DLA electron as compared with the non-DLA one, and the resonance condition is approximately preserved over the most part of the propagation distance. Due to the detuning between $\langle \omega_d \rangle$ and $\omega_{\beta}$ as shown in figure 1(c), the energy gain directly from the laser field of DLA electron saturates at the later times as shown in figure 1(d). After establishing the importance of large initial transverse energy for effective direct laser acceleration, we now proceed to demonstrating that this condition can be fulfilled using ionization injection into a bubble.

### 3. Particle-in-cell simulations of ionization injection in a LWDA

In this section, we use first-principles self-consistent relativistic 2D PIC code VLPL [43] to simulate ionization injection and acceleration of electrons to GeV energies in a LWDA. The schematic of a proposed LWDA is shown in figure 2 (see caption for simulations parameters). Multi-terawatt ($P_{\text{pump}} = 96$ TW and $P_{\text{DLA}} = 28$ TW) pump and the time-delayed DLA pulses are assumed in the simulation. Instead of engineering a density bump [20] for injecting electrons with large transverse energy, the injection due to the ionization of high-Z oxygen ions ($O^{7+} \rightarrow O^{8+}$) is modeled in the simulation. The 100 $\mu$m-long gas mixture region consisting of 90% He and 10% O$_2$ is shown as a dark area in figure 2.

The leading edge of the pump pulse fully ionizes helium and the low-charge states of oxygen ions, thereby creating a background plasma with the density $n_0 = 4.0 \times 10^{18}$ cm$^{-3}$ which is pushed aside by the pump pulse to create a plasma bubble. The K-shell oxygen’s electrons are produced via ionization close to the peak of the pump pulse intensity.
Even after the electrons reach the middle, ionization potential for \( mc \) shows positive correlation, \( \sim 770 \) MeV, and very close to the longi-

tudinal velocity of the DLA electrons. The expansion of the plasma bubble [33, 34] observed by comparing the top panels of figures 3(a) and (b) also plays a role in maintaining excellent overlap between the DLA pulse and the injected electrons near the middle of the plasma bubble.

Close observation of figure 3(b) and its zoomed-in version in figure 4(a) shows that DLA and non-DLA particles are spatially separated in \( x \). This is the consequence of equation (3) which predicts that DLA electrons with large betatron amplitudes advance less through the bubble than the non-DLA electrons. The resulting phase space bifurcation in the LWDA bubble is apparent from figure 4(a), where the injected electrons are color-coded according their total energy \( \gamma mc^2 \), and the vertical black line indicates the center of plasma bubble. The high-energy DLA group of electrons is located behind the lower-energy non-DLA group, which is already in the decelerating region of the bubble.

The total energy spectrum of the accelerated electrons are plotted in figure 4(b). The spectrum has two peaks which represent the DLA \( \gamma^{DLA} mc^2 \approx 770 \) MeV and non-DLA electrons \( \gamma^{ADK} mc^2 \approx 450 \) MeV, respectively. The DLA effect does not compromise the beam’s energy spread; in fact, the energy distribution of the DLA electrons is considerably lower than that of the non-DLA electrons.

Below we present a quantitative statistics of the ionized electrons. The number of trapped electrons is about 90% of all electrons released by oxygen ionization. There are about 13% of electrons undergoing significant DLA within the group of trapped electrons or about 11% within the group of all electrons released by ionization. DLA electrons form a sub-population of high transverse energy electrons, that were born either off-axis or off-peak phase. The ADK ionization rate is
relatively small when it is off-axis or off-peak phase. So the number of DLA electrons is smaller than the number of non-DLA electrons.

Due to the 2D geometry, we can only roughly estimate the charge yield. The beam density is $n \approx 8 \times 10^{17}$ cm$^{-3}$ at the propagation distance $x = 2.6$ mm as shown in figure 4. The length of the beam is about $L_b \approx 6 \mu$m and the radius is about $r_b \approx 4 \mu$m. We estimate that there is about 40$pC$ charge in the beam.

Another intriguing difference between DLA and non-DLA electrons is revealed in figure 4(c) which shows the bifurcated ($\gamma, \epsilon_\perp$) phase space of the accelerated electrons. The DLA group exhibits a clear positive correlation between $\gamma$ and $\epsilon_\perp$, while there is no such correlation for the non-DLA group. Both the double-peak phase spectrum and the bifurcated phase space are reminiscent of the earlier results [20] obtained using the density bump injection. However, the key finding of the present work is that the synergistic LWFA and DLA mechanisms can be realized in an accelerator with ionization injection. In the next section we examine the mechanisms responsible for providing large initial transverse energies to the electrons produced using tunneling ionization.

4. Mechanisms of ionization injection

To understand how laser-ionized electrons can acquire large transverse energy necessary for DLA, we need to recall the specifics of ionizing an atom in a laser field that greatly exceeds the atomic electric field $E_0 = e r_e^2 \approx 5.1$ GV cm$^{-1}$, where $r_e = e^2/m_e c^2$ is the classical electron radius. According to the ADK tunneling ionization model [44–46], the ionization rate is given by the following expression:

$$W(t) = \omega_c e^{(E_{ion}/E_{L}(t))^d} \exp \left[-(E_{ion}/E_{L}(t))^e\right],$$

where $\omega_c = \alpha c r_e$ is the atomic frequency unit, $\alpha = 1/137$ is the fine structure constant, and for the $O^{7+}$ oxygen ionization we estimate that $C \approx 8.4 \times 10^4$, $d \approx 1$ and $E_{ion} \approx 1.7 \times 10^3$ GV cm$^{-1}$. ADK tunneling ionization model implemented in VLPL [45, 46] assumes that the ionization rate is given by equation (4).

From equation (4) we conclude that for the peak on-axis electric field of the laser $E_0 = 3.5$mVcm$^{-1}$ and the pulse duration of $\tau_{pump} = 20$ fs, the product $W(E_0)\tau_{pump} \gg 1$. This means that an $O^{7+}$ ion located on the laser axis is ionized to its $O^{8+}$ state with nearly 100% probability. This also implies that an atom experiencing a weaker instantaneous field $E_L(t) < E_0$ can also lose an electron with significant probability. In the near-static tunneling limit of $\omega_t \ll \omega_c$ electron tunneling may follow according to the following scenarios: (a) at $z = 0$ (off-axis tunneling), or (b) at $z = 0$, but at the electric field’s phase $\phi$ that does not correspond to it’s maximum (off-peak phase ionization). Of course, all intermediate scenarios are also possible, so the (a) and (b) are the two limiting cases that supply ionization-produced electrons with finite transverse energy $\epsilon_\perp$ necessary for DLA acceleration. The scenarios (a) and (b) are illustrated by figures 5(a) and 6(a) respectively.

The motion of an ionized electron born at rest inside the pump pulse can be broken up into three stages: (i) ionization and direct interaction with the pump laser pulse, (ii) initial trapping in the bubble, and (iii) final acceleration by the combination of LWFA and DLA mechanisms. The first two stages are very short and result in the electron’s energy gain of the order of $\gamma_0 m_e c^2$. The third stage is the longest one; it results in the accumulation of the work $A_{m_e c^2}$ done by the wake, and work $A_L$ done by the laser for the same representative electrons as in (a). Simulation parameters: same as in figure 2.

Figure 5. The evolution of ionization-injected electrons in the plasma bubble. (a) Trajectories of the representative DLA (red solid curve) and non-DLA (blue solid curve) electrons. Colored dotted curves: the labelled $e\Psi/m_e c^2$ = const contours of the wake’s potential. Black dashed curves: $E/L^{max} = 0.45$ contour inside which 99% of ionization events takes place. (b)–(e) The long-term evolution of the transverse momentum $p_\perp$, relativistic factor $\gamma$, the work $A_m$ done by the wake, and work $A_L$ done by the laser for the same representative electrons as in (a). Simulation parameters: same as in figure 2.
in the final energy gain exceeding $2\gamma_0^2m_ec^2$. Because the third stage of the electron acceleration in an LWDA was previously analyzed in some detail [20], below we concentrate mostly on the first and second acceleration stages, as well as on the earliest times of the third stage.

During the first stage of the duration $\Delta \tau \sim \tau_{\text{pump}}$ the electron born at $t = t_i$ at $(x = x_i, z = z_i)$ interacts primarily with the pump pulse. This interaction is best described using the (approximate) conservation of the transverse canonical momentum: 

$$p_z(t)/m_ec - a_z(z(t), t) = p_z(t_i)/m_ec - a_z(z_i, t_i),$$

where $a_z = eA_z/m_ec$ is the normalized canonical momentum of the laser. This approximation is valid as long as the laser spot size satisfies $w_{\text{pump}} \gg z_{\text{wiggles}}$, where $z_{\text{wiggles}}$ is the wiggling amplitude of the newly-ionized electron in the laser field. Combining the $a_z(t_i) = 0$ for $t > t_i + \tau_{\text{pump}}$ condition with $p_z(t_i) = 0$, we obtain $p_z/m_ec = -a_z(z_i, t_i)$ at the end of the first stage.

Assuming that $A_z = cg(z)E_0 \cos \omega_L(t - x/v_{ph})/\omega_L$, where $g(z)$ is the transverse laser profile normalized as $g(z = 0) = 1$, we obtain [40, 41]

$$p_z = -g(z_i)\frac{eE_0}{mc\omega_L} \cos \phi_i,$$  

(5)

where $\phi_i = \omega_L(t_i - x_i/v_{ph})$ is the laser phase at the moment of electron’s tunneling from an oxygen ion in the electric field of the magnitude $|E| = E_0|g(z_i)|\sin \phi_i$. By definition, the peak-phase ionization corresponds to $\phi_i = \pm \pi/2$ and vanishing transverse momentum $p_z = 0$ while the off-peak ionization corresponds to $\phi_i = \pm \pi/2$ and $p_z \neq 0$. Therefore, those electrons born far off-axis are likely to be produced by peak-phase ionization and to have small $p_z$. On the other hand, the on-axis electrons can be ionized during the off-peak phase of the laser and have a relativistic $p_z \sim eE_0/m_ec\omega_L$. However, both off-axis and off-peak electrons can have a substantial initial transverse energy $\epsilon_{0z} = p_z^2/2m_e + m_e\omega_L^2p_z^2/4$ (where $z_0 = z_i$) that is necessary for effective DLA.

The second stage involves electron’s motion toward the back of the bubble and its subsequent trapping. Because of the brevity of the first stage, we assume that the electron’s initial conditions established for the second stage are $(z_0, p_{0z}, x_i, p_{0x}) = (0)$. Assuming that the bubble does not have sufficient time to evolve during the second stage, we can take advantage of the conservation of the moving frame Hamiltonian (MFH) [29, 34, 42] given by

$$H = \gamma m_ec^2 - v_{ph}p_x - e\Psi$$  

(6)

where $\Psi = \Psi_s - \Phi$ is the wake potential constructed from its vector potential and scalar potentials $A_s$ and $\Phi$, respectively. Using the results of the PIC simulations, we can approximately calculate $\Psi_i(z, x)$ at any instance of time according to $\Psi = \int_{\text{min}}^{\text{max}} E_x d\zeta$, where $E_x$ is the longitudinal electric field, and the integration is carried out over the entire moving computational window that encompasses the plasma bubble. The contours of constant $e\Psi_i(z, x)/m_ec^2$ calculated at $x = 120 \mu$m inside the ionization region shown in figure 2 are presented in figures 5(a) and 6(a). For this particular case we have found that the maximum value of $\Psi$ at the center of the bubble is $\Psi_{\text{max}} \approx 3.1 m_ec^2/e$ while its minimum value at the bottom of the bubble is $\Psi_{\text{min}} \approx 0.1 m_ec^2/e$.

It is instructive to simplify the expression for the MFH in the two important limits: at the end of the first acceleration stage, when $p_z/m_ec \ll \gamma_0 \sim 1$, and at the end of the second stage, when $\gamma_{\beta} \ll \gamma_0 \ll \gamma_{\beta}^2$. In the former case we can assume that $H_0 \approx \gamma_0 m_ec^2 - e\Psi_i(z, x)$ while in the latter case $H_f \approx -e\Psi_i(z, x)$, where $(\zeta_i, x_i)$ are the coordinates of electrons birth/trapping inside the plasma bubble. From $H_0 = H_f$ we derive the following trapping condition for the electrons:

\begin{align*}
\end{align*}
\[
\frac{e(\Psi_i - \Psi_f)}{mc^2} \approx \gamma_0 \sim 1,
\]
where \(\Psi_i \equiv \Psi_i(\zeta_i, z_i)\) and \(\Psi_f \equiv \Psi_f(\zeta_f, z_f)\).

The constant-\(\Psi\) contours can be used for a simple graphical interpretation of the trapping condition given by equation (7). If an electron is born on the \(\Psi_i\) contour, then it will slip out of the bubble if \(\Psi_i < \Psi_{\text{min}} + \gamma_0 mc^2/e\). This condition is exemplified by a representative magenta-colored electron shown in figure 6(a) born at the leading edge of the pump. This electron, which starts insuffficiently deep inside the bubble with \(\Psi_i \approx 0.5m_c c^2/e\), does not get trapped inside the bubble. On the other hand, all other representative electrons shown in figures 5 and 6 that are born deep inside the bubble (\(\Psi_i > 1.2m_c c^2/e\)) end up trapped inside the bubble because the trapping condition \(\Psi_i > \Psi_{\text{min}} + \gamma_0 mc^2/e\) is satisfied for them.

Now we consider the third acceleration stage involving the long-term interaction of the trapped electrons with the DLA pulse and with the bubble’s wakefield. The trajectories of two typical trapped electrons are shown in figure 5(a) over a distance of \(x < 0.8\) mm after their ionization. The electrons are chosen to belong to the DLA (red) and non-DLA (blue) groups. The pump laser’s intensity contour shown with a dashed line was chosen in such a way that 99\% of all ionization events take place inside the contour based on ADK the tunneling ionization model [44, 45]. We observe that the non-DLA electron is born near the axis and during the peak ionization phase \(\phi_i \approx \pi/2\). Therefore, this electron does not acquire any significant initial transverse energy \(\epsilon_{0,1}\) during the first acceleration stage. Even though the non-DLA electron spatially overlaps with the DLA laser pulse as illustrated in figure 5(a), its interaction with the laser is weak because its initial transverse energy is small. On the other hand, the DLA electron is produced via off-axis peak-phase ionization at \(z_i \approx 11\lambda_a\) with considerable \(\epsilon_{0,1}\).

The long-time acceleration of these two representative electrons shown confirms their classification as DLA and non-DLA. The energy gains \(A_w = -\int E \cdot \mathbf{v} dt\) and \(A_L = -\int E_{\mathbf{w}} dt\) from the wake are plotted in figures 5(d) and (e), respectively. The DLA electron gains much more energy \((\Delta A_L \approx 700m_c^2)\) directly from the laser than non-DLA electron. Meanwhile, the DLA electron also gains more energy \((\Delta A_w \approx 100m_c^2)\) from the wake than a non-DLA electron because of the delayed dephasing predicted by equation (3). The delayed dephasing of the DLA electron with respect to the non-DLA one is observed by comparing the peaks of the two \(A_w(x)\) curves in figure 5(d). The non-DLA electrons lose about 50–100 MeV due to the dephasing. The combination of these two factors provide the DLA electron with much larger higher peak energy \(\gamma_0 mc^2\) as shown in figure 5(c).

Two more electron injection and acceleration scenarios are illustrated in figure 6, where the trajectories of a non-DLA (brown-colored) and DLA (green-colored) trapped electrons are shown in figure 6(a). The non-DLA electron is born near the trailing edge of the pump pulse deep inside the bubble at \(\Psi_i \approx 2.5m_c c^2/e\). The conservation of the MFH expressed by equation (7) implies that the electron does not reach the back of the bubble and, therefore, does not overlap with the DLA pulse. The direct laser energy gain \(A_L\) is, therefore, negligible, i.e. even smaller than for the non-DLA electron analyzed in figure 5.

The DLA electron shown in figure 6 exemplify the electrons injected via the off-peak phase tunneling [47]. Even though the electron is produced by laser ionization on-axis, its trajectory shown in figure 6(a) clearly indicates that it has a large transverse momentum after the first acceleration stage. The initial transverse momentum of the electron is estimated to be \(p_{\perp} \approx 2.2m_c c\). Because of its unusual trajectory that involves several bounces off the edge of the plasma bubble before overlapping with the DLA pulse and undergoing further acceleration, we refer to such particles as ‘ricochet’ electrons. By following the long-term acceleration of the ricochet DLA electron shown in figures 6(b)–(e), we conclude that the efficiency of DLA is comparable for the electrons produced via off-axis and off-peak tunneling. Therefore, we conclude that the DLA electrons injected into the bubble via ionization injection roughly belong to two categories: the off-axis ionized and the off-peak phase ionized (ricochet) electrons.

5. Conclusion

In conclusion, we have demonstrated that ionization injection is suitable for a laser wakefield and direct accelerator (LWDA) that relies on the hybrid laser wakefield and direct laser acceleration mechanism for achieving the highest energy gain. We find that the electrons’ energy spectrum is split into two peaks corresponding to two sub-populations: the higher-energy DLA and the lower-energy non-DLA particles. By tracking several electrons with different initial condition, we demonstrate that DLA electrons born inside the plasma bubble must have significant transverse energy. Two ways of gaining such energy are discovered using PIC simulations: electrons must be generated either via off-axis of via off-peak phase tunneling. With the introduction of ionization injection, the hybrid laser wakefield and direct laser plasma accelerator may potentially become more stable and controllable. High energy DLA electrons generated in LWDA may have future applications as the sources of x-rays.

Acknowledgments

This work was supported by DOE grants DE-SC0007889 and DE-SC0010622, and by an AFOSR grant FA9550-14-1-0045. The authors thank the Texas Advanced Computing Center for providing HPC resources.

References


[38] Or E et al 2007 Phys. Rev. Lett. 98 084801


