Colliding ionization injection in a plasma wakefield accelerator

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Abstract
A new scheme of generating high quality electron bunches via ionization injection triggered by an counter propagating laser pulse inside a beam driven plasma wake is proposed and examined via two-dimensional particle-in-cell (PIC) simulations. This scheme has two major advantages: first, the injection distance is easily tunable by varying the launching time or the focal position of the laser pulse; second, the electrons in each injected slice are released at nearly the same time. Both factors can significantly reduce the phase space mixing during the ionization injection process (Xu et al 2014 Phys. Rev. Lett. 112 035003, Xu et al 2014 Phys. Rev. Spec. Top.: Accel. Beams 17 061301, Li et al 2013 Phys. Rev. Lett. 111 015003), leading to very small energy spreads (\(~10\) keV for slice, \(\sim100\) keV for the whole bunch) and very small normalized emittance (\(\sim\)few nm). As an example, a 4.5 fs 0.4 pC electron bunch with normalized emittance of 3.3 nm, slice energy spread of 13 keV, absolute energy spread of 80 keV, and a brightness of $7.2 \times 10^{18} \text{A m}^{-2}\text{rad}^{-2}$ is obtained under realistic conditions. This scheme may have potential applications for future compact coherent light sources.

Keywords: plasma wakefield accelerator, ionization injection, low slice energy spread, electron dynamics

(Some figures may appear in colour only in the online journal)
[1, 2]. To significantly reduce the injection distance, a transverse colliding geometry [3] was also proposed, which shows that injection distance of few μm can be achieved, resulting in very low slice energy spread (∼10 keV) and low emittance (few nm). In this paper we will propose a simpler scheme using only one counter-propagating laser pulse to achieve low energy spread and low emittance injection.

In this scheme, the injected electrons are ionized via tunnel ionization at the focus of a counter propagating laser pulse in a beam driven plasma wake. Such geometry is very similar to the typical layout of Thomson Scattering x-ray sources, making it relatively easier to implement. In the following sections, this scheme will be examined carefully through theoretical analysis and 2D PIC simulations. It turns out that this scheme has two major advantages comparing with the co-propagating case: first, the injection distance is easily tunable by varying the launching time or the focal position of the laser pulse; second, the electrons in each injected slice are released at nearly the same time. Both factors can significantly reduce the phase space mixing during the ionization injection process [1, 2], leading to very small energy spreads (∼10 keV for slice, ∼100 keV for the whole bunch) and very small normalized emittance (∼few nm).

2. Theoretical analysis and simulations

The mechanism for colliding ionization injection is explored using the PIC code OSIRIS [30] in 2D Cartesian coordinates with a fixed window. In the simulations, the drive beam’s propagating direction is chosen as the z axis, and one of the transverse directions is chosen as the x axis. The whole simulation box is of a size 610 × 101 μm, with 14 400 × 3200 cells along the z and x direction respectively. The ADK (Ammosov–Delone–Krainov) ionization model is employed to simulate the ionization process [31].

In the simulations, a pre-ionized plasma with an electron density of \( n_e = 2.4 \times 10^{17} \text{cm}^{-3} \) is used, and the injection electrons are provided by a neutral He gas with a density of \( n_{\text{He}} = 1.34 \times 10^{18} \text{cm}^{-3} \). 4 particles for electrons and 8 particles for heliums are initialized in each cell. A 100 MeV electron beam with the transverse and longitudinal dimensions \( \sigma_e = 3.8 \mu\text{m}, \sigma_z = 6 \mu\text{m} \), and \( n_p = [N/(2\pi)^{3/2}\sigma_e^2\sigma_z^2]\exp(-r^2/2\sigma_e^2 - z^2/2\sigma_z^2) = 5.1 \times 10^{17} \text{cm}^{-2} \) propagates through the plasma and excites a blowout wakefield with the wavelength of \( \lambda_p \approx 80 \mu\text{m} \). The beam’s self-electric field (≈30 GV m\(^{-1}\)) does not ionize the helium atoms. Meanwhile, a counter propagating laser pulse with the polarization along the x direction is synchronized with the electron beam. The laser has a normalized vector potential \( a_0 = 0.03 \), a pulse duration \( \tau = 20 \text{fs} \), and a focal spot size \( w_0 = 2 \mu\text{m} \). These parameters correspond to a focused intensity of \( 2 \times 10^{15} \text{W cm}^{-2} \) for \( \lambda_0 = 800 \text{nm} \).

Since the laser’s propagation direction is opposite to the beam driver, ionization occurs within a quite long phase interval in the wake. The length of this interval is about two times the length of the ionization region of the laser. In our simulation, this length is about 100 μm, which is much longer than that in the typical co-propagating injection case, where ionization fills a relatively small phase interval (about the laser pulse duration). Based on the 3D analytical trapping condition \( \Delta \psi \approx \psi - \psi_{\text{init}} < -1 \) [1, 25], the trapping phase can be estimated to be about 45 μm in our simulation, where \( \psi = e(\phi - A_z)mc^2 \) is the normalized wake potential and \( \psi_{\text{init}} \) is the initial wake potential when an electron is released. By varying the launching time or the focal position of the laser pulse to adjust the overlap of the trapping and ionization phases, the injection distance can be made short enough to produce an electron bunch with very small transverse emittance.

As shown in figure 1(a), the ionization in our simulation starts within the acceleration phase where \( \partial^2\psi/\partial t^2 \psi < 0 \). In figure 1(b), lineouts of \( \psi \) (black solid curve) and the He\(^+\) ion density (blue dashed curve) along the green dashed line of figure 1(a) are plotted. On the \( \psi \) curve one can find that \( \psi_{\text{init}} \approx -0.5 \), therefore electrons ionized at \( \xi \) with \( \psi(\xi) > 0.5 \) can get trapped, as marked in green on figure 1(b). The ionization region is marked in purple, and there is a narrow overlap (in red) between ionization (purple) and trapping regions (green) where ionized electrons can be trapped by the wake. By varying the laser focal position or launching time, this overlap can be easily tuned to optimize the injection distance, which is critical for reaching very low energy spread and emittances. The total charge of injected beam can also be tuned by varying the neutral helium density.

Figure 2 illustrates the injection process in detail. Figure 2(a) shows the back moving laser and the plasma wake at a time well before ionization occurring; figure 2(b) shows the laser reaching near its focus and starting to ionize the He atoms. The freed electrons then are rapidly accelerated inside the wake as they slip backwards to the back of the cavity. Figure 2(c) shows the state of the trapped electrons at the tail of the first cavity after the laser passing through. We note that only a fraction of all the freed electrons finally get trapped due to the restriction of the injection condition.

Figures 3(a) and (b) show the transverse phase space \((x-p_x)\) and longitudinal phase space \((z-p_z)\) of injected electrons about 550 fs after ionization, respectively. The injected beam has an ultralow normalized transverse emittance \( \epsilon_{\text{xu}} \) (defined as \( \sqrt{\langle x^2 \rangle \langle p_x^2 \rangle - \langle x \rangle^2 \langle p_x \rangle^2} \)) of about 3.3 nm, where \( \langle \cdot \rangle \) represents averaging over the beam distribution, \( m_e \) the electron mass and c the speed of light. At this point, the injected beam has reached an average energy of 6.67 MeV, with a rms energy spread of 80 keV and a slice rms energy spread of ∼13 keV (assuming 0.5 μm slice thickness). The total injected charge is about 0.4 pC with a pulse duration of 4.5 fs (rms), and the beam brightness \( B_{\text{w}} \approx 2I_{\text{w}}/\epsilon_{\text{w}}^2 \approx 7.2 \times 10^{18} \text{m}^{-2} \text{rad}^{-2} \text{s}^{-1} \), is about 3 orders of magnitude larger than that in the Linac Coherent Light Source (LCLS) [32]. We note that the charge can be further increased by using a larger laser focal spot, and the energy spread can be further reduced by optimizing beam loading or by using a longer wavelength wake.

To ensure the very small emittance \( \epsilon_{\text{xu}} \) and small energy spread, several key factors need to be considered. First, the initial thermal emittance \( \epsilon_{\text{th}} \) should be as small as
possible. In the beam driven plasma wakes, the beam’s self electric field is too low to ionize the doping gas (e.g. helium), while an injector laser of 800 nm with low intensity (e.g. $a_0 = 0.03$) and small focal spot size can be used to trigger the ionization of the doping gas to obtain beams with very small initial momentum and beam size.

The second key factor is to reduce the the injection distance [1, 2, 33]. Long injection distance can lead to significant phase mixing and emittance growth due to the fact that electrons born at different times can have different betatron phases. In the colliding ionization injection proposed here, the injection distance can be greatly reduced by tuning the overlap between the ionization region and the trapping region. For example, in the simulation given above, the injection distance is only about 1/4 of the whole ionization length, which is much shorter than that in a similar co-propagating injection scheme, where ionization occurs approximately at fixed phase (usually near where $\psi$ is maximum) with an injection distance close to the ionization length.

Regarding the energy spread of the injected beam, there are three sources: initial momentum spread due to ionization process (proportional to $a_0$), the spread of the longitudinal
The acceleration phase (spread in $E_z$) and the slice energy spread. The effect of $E_z$ can be mitigated through beam loading or shorter bunch length. However, the slice energy spread is mainly determined by the injection process itself, which can be very different for different schemes. It turns out that the slice energy spread can be very small in the colliding ionization injection scheme.

It is known that $\psi$ in the ion cavity can be expressed as $\psi(\xi, r) \approx [r_b^2(\xi) - r^2]/4$, where $r_b(\xi)$ is the normalized radius of the blowout at different $\xi$ and $r_b(\xi) = r_m - \xi^2$, and $r_m$ is the largest blowout radius \cite{1, 15, 16}. By applying the trapping condition $\delta \psi \approx -1$, it is straightforward to obtain:

$$\xi_f^2 + r_f^2 = 4 + \xi_i^2 + r_i^2$$

(1)

where the subscript f and i represent the final and initial positions, respectively. In most cases, especially when the injector laser’s spot size is much smaller than the blowout radius, the effect of $r_f$ and $r_i$ can be neglected. So equation (1) can be simplified as:

$$\xi_f = \sqrt{4 + \xi_i^2}$$

(2)

It indicates that the $\xi_f$ has a simple corresponding relation with $\xi_i$. In the co-propagating injection case, $\xi_i$ is almost fixed during the ionization process. Therefore, each final slice (each $\xi_f$) of the injected beam is composed of electrons ionized at different times. This leads to the relative large energy spread of electrons within a single slice. However, in the colliding injection case, electrons injected in each slice are born at nearly the same time. As a result, each final slice $\xi_f$ of electrons has extremely small energy spread as well as emittance.

To verify the analysis above in detail, we also simulate the injection process of the co-propagating ionization injection scheme for comparison. In this case, an injection laser pulse propagates collinearly at an optimum distance (about 78 fs) behind the beam driver, where $E_z = 0$. The parameters of the drive beam, injection laser and pre-ionized plasma are the same as the simulation for the colliding ionization injection described above. The neutral helium density is $3.1 \times 10^{16} \text{cm}^{-3}$, which is different from the colliding propagation case, for the purpose of obtaining similar injected charge (about 0.45 pC).

Figures 3(c) and (d) show the phase space of injected electrons of different planes about 560 fs after ionization via the co-propagating approach. It is shown that the transverse phase mixing in the co-propagating case is much more severe than that in the colliding scheme and its final emittance is about 10.5 nm. Figure 3(d) shows that the electron’s slice energy is also larger, about 0.4 MeV and their total energy spread is about 0.5 MeV. Figure 4 further compares the phase space of these two schemes at about 130 fs after the onset of injection. As seen in figure 4(b), as the injection is ongoing, the first ionized electrons have rotated around $3/4 \pi$, while the final ionized electrons have just been released. However, in our proposed colliding scheme, the injection has already finished, and the phase difference $\Delta \phi$ is much smaller than that in the co-propagating case.

To obtain the extremely low transverse emittance in the colliding injection scheme, the key point is to vary the launching time or the focal position of the injection laser pulse to optimize the injection distance. Here we study the effect of this issue by changing the focal position $z_f$. We define the $z_f = 0$ as the laser focuses at $E_z = 0$ when it encounters with the $\psi_{\text{max}}$ of the wake, and $z_f < 0$ as the focal position at $E_z > 0$.
The simulation parameters are identical to those of figure 3(a), except that the neutral helium density is set as \(5 \times 10^{16} \text{ cm}^{-3}\). Four cases of \(z_f = 0, 20, 35, \text{ and } -20 \mu m\) are simulated. As \(z_f\) increases, the overlap between the phase area of ionization region and the trapping region is generally reduced, and the injection distance also become shorter, leading to the reduction of final total emittance. This is consistent to the fact that the emittance of \(z_f = 35 \mu m\) is the smallest, as shown in figure 5(a). Through more simulation test, it is found that the final emittance can be less than 7 nm as long as the focal position satisfies \(z_f \leq 50 \mu m\).

Figures 5(b)–(e) illustrate the longitudinal phase space of \(z_f = 20 \mu m\) and \(-20 \mu m\), respectively. If the laser pulse converges upon the point \(E_z = 0\), electrons at both \(\xi_i\) and \(-\xi_i\) are ionized. According to equation (2), they will finally be trapped at the same acceleration phase \(\xi_f\). However, they will experience different injection distances. Electrons born at \(-\xi_i\) will be accelerated backward and then be decelerated when they enter the phase of \(E_z < 0\), and arrive at \(\xi_i\) with momentum close to its initial value at ionization. So obviously, electrons born at \(\xi_i\) arrive at the final trapped phase \(\xi_f\) earlier than those born at \(-\xi_i\). Therefore, in figures 5(b), (c) and (e), some slices have double energies. Also because of the shorter injection distance for electrons born at \(\xi_i > 0\), the emittance of \(z_f = 20 \mu m\) is relatively smaller than that of \(z_f = -20 \mu m\), as shown in figure 5(a).

3. Conclusions

A new ionization injection scheme is proposed in the context of beam driven plasma wakefield accelerators. In this scheme, the injected electrons are ionized via tunnel ionization at the focus of a counter propagating laser pulse in a beam driven plasma wake. Such geometry is very similar to the typical layout of Thomson scattering x-ray sources, making it relatively easier to implement. There are two major advantages in this scheme: first, the injection distance is easily tunable by varying the launching time or the focal position of the laser pulse; second, the electrons in each injected slice are released at nearly the same time. Both factors can significantly reduce the phase space mixing during the ionization injection process[1–3], leading to very small energy spreads (\(\sim 10\) keV for slice, \(\sim 100\) keV for the whole bunch) and very small normalized emittance (\(\sim\)few nm), making this novel scheme a potential approach for future compact coherent light sources.

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