Electron injection and emittance control by transverse colliding pulses in a laser-plasma accelerator

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A method to inject electron beams with controllable transverse emittances in a laser-plasma accelerators is proposed and analyzed. It uses two colliding laser pulses that propagate transversely to the plasma wave. For colliding pulses with equal frequencies, a beam with very low emittance is generated when the collision is close to the density peak of the plasma wave. Electrons near the axis are accelerated longitudinally by the ponderomotive force of the colliding pulses, accelerated transversely by the beat wave, and subsequently injected into the second bucket of the wake. Ionization is used to increase the transverse injection area and the final trapped charge. Simulations show that the transverse emittance can be less than the 0.1 mm mrad level, which is important for many applications. For colliding laser pulses with different frequencies, the beat wave can produce asymmetric injection, which can enhance betatron radiation generated by the electron beam.

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Laser-plasma acceleration (LPA), where an intense laser drives a plasma wave, is an active research field due to the ability of a plasma wave (wake) to sustain accelerating gradients much greater than conventional accelerators [1]. The potential applications of this technology include linear colliders [2] and light sources [3]. Enabling these applications requires the generation of high brightness electron beams. Quasimonoenergetic beams with percent-level relative energy spreads have been demonstrated [4,5]. Reduction of the electron beam energy spread and transverse emittance is critical for many applications, and significant research has focused on controlled injection of electrons into the plasma wave to improve the electron beam quality [6–19]. Recent LPA measurements have found normalized transverse emittances as low as 0.1 μm , as inferred from betatron radiation [20–22] and quadrupole scans [23]. Ultracold transverse injection has been theoretically predicted by using ionization injection in a beam-driven plasma wakefield accelerator [24]. For an LPA using ionization injection, a limiting contribution to the emittance is the large transverse field of the ionizing laser, which

generates relatively large transverse electron momenta via the ionization process [19].

In this paper, we propose and analyze the transverse colliding pulse injection (TCPI) method for laser-plasma accelerators (LPAs), in which the transverse momentum spread can be controlled and reduced by more than an order of magnitude compared with existing optical injection methods [19]. This method relies on generating a beat wave near the density peak in the plasma wave using transversely propagating laser pulses. We find that with TCPI, the transverse momentum spread of the accelerated electron beam can be much smaller compared with injection using a longitudinal colliding pulse injection scheme. In addition, by the use of ionization, we can increase the trapped beam charge, while keeping the final emittance small. By tuning the laser frequencies, the injection can be transversely asymmetric, which can control and enhance betatron radiation by the electron beam LPAs [25].

In general, to obtain a small transverse emittance beam in LPA it is desirable that the injection process satisfy two basic conditions: first, that the initial transverse momentum spread of the injected electrons should be as small as possible; second, that the initial transverse position of the injected beams inside the accelerated wake should be as close to the transverse center of the wake as possible, since electrons injected off axis will be accelerated by the transverse wakefield, resulting in large transverse emittance. The TCPI method fulfills these two conditions. A schematic of this method is shown in Fig. 1(a). In TCPI,

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FIG. 1. (a) Plasma density and laser intensity distribution at $t = 200$ fs. (b) Phase space distribution (P_x - P_y) of trapped preionized and laser-ionized electrons after the drive pulse propagated 0.79 mm. The right red curve shows the transverse momentum spread after longitudinal integration. The lower black curve shows the beam energy spread.

a drive laser pulse is used to excite a plasma wake without self-injection or ionization injection (a partially stripped nitrogen gas is considered). Two counterstreaming laser pulses (injection pulses), propagating transversely to the drive pulse, collide with each other at an appropriate phase inside the wake behind the drive pulse. To obtain a low emittance beam, transverse pulses with the same frequency should be used, the collision point should be close to the density peak of the wake, and the two transverse pulses should be polarized along the propagation direction of the drive laser. To obtain transversely asymmetric injection, transverse pulses with different frequencies can be used to generate a beat wave with a finite phase velocity in the transverse direction, which can strongly kick the electrons transversely.

To study TCPI, two-dimensional particle-in-cell simulations were performed using the codes VORPAL [26] and VLPL [27], and results were benchmarked between the two codes. In these simulations, a linearly polarized drive pulse with Gaussian profiles in both the transverse and longitudinal directions is launched into a plasma from the left boundary of the simulation box. Two identical linearly polarized injection pulses are launched from the transverse boundaries of the simulation box with their electric fields polarized along the x direction (the propagation direction of the drive pulse).

High quality transverse colliding pulse injection was observed using a drive pulse length of $L_0 = 6.0\lambda_0$ and transverse size of $W_0 = 10\lambda_0$, where $\lambda_0 = 0.8 \mu\text{m}$ is the wavelength of the drive pulse. The normalized field of the drive pulse is $a_0 = eA/m_e c^2 = 1.5$ and $a \propto a_0 \exp[-(x-ct)^2/L^2] \exp(-r^2/W^2)$. The injection pulses have longitudinal lengths $L_1 = L_2 = 3.0\lambda_0$ and transverse sizes $W_1 = W_2 = 3.0\lambda_0$ (tightly focused). The two transverse pulses have the same wavelength $\lambda_0 = 0.8 \mu\text{m}$ and intensities $a_1 = a_2 = 0.8$. Their propagation axis is $40\lambda_0$ away from the left boundary of the simulation box, also the axis of the drive pulse plasma wake. The plasma density was chosen to allow resonant excitation of the plasma wake by the drive pulse, at $n_{\text{pre-e}} = 0.001n_c$, where $n_c = \pi m_e c^2 / \lambda_0^2 e^2 \approx 1.74 \times 10^{21} / \text{cm}^3$ is the critical plasma density for the laser pulse. The preionized plasma had a density profile with a linear up ramp from $x = 2\lambda_0$ to $x = 10\lambda_0$, then a flattop to $x = 1000\lambda_0$. The short up ramp length is chosen to reduce computational cost and its length does not affect the injection. To increase injected charge, a small fraction of neutral nitrogen was mixed into the preionized plasma near the injection location. The density of the nitrogen atoms is $n_N = 2.0 \times 10^{-6}n_c$ (0.2% of the preionized electrons), which will not affect the plasma wave structure or laser pulse focusing [11,16–19]. The nitrogen begins at $x = 30\lambda_0$ and ends at $x = 50\lambda_0$ with a $15\lambda_0$ flattop region in the middle. The simulation box has a length of $100\lambda_0$ and width of $140\lambda_0$ (within the perfectly matched absorbing boundary layers). A longitudinal and transverse resolution of $dx = dy = 0.05\lambda_0$ is used for numerical dispersion accuracy for both the drive and injection pulses, with a moving window in the longitudinal direction.

Figure 1(a) shows the plasma density and the intensity distribution of the three pulses at an early time $t = 75T_0 = 75\lambda_0/c$ before the two transverse pulses collided. For these laser-plasma parameters, the three pulses each generate a wakefield. The amplitudes of each individual wake are below the threshold for self-injection or ionization injection. Hence, without collision of the injection pulses no beam is observed. After collision, at the end of the simulation (0.79 mm) the final electron phase space distribution is shown in Fig. 1(b), where $6.38 \times 10^6 / \mu\text{m}$ have been injected into the second wake bucket. The final beam transverse full-width-at-half-maximum (FWHM) momentum spread is $\delta P_y \approx 0.1m_e c$. The beam is quasi-monoenergetic with peak energy of 29.32 MeV and FWHM energy spread $\delta E \approx 3.84$ MeV.

Previous simulations [1,7,13,28] show that the bunches from this or other LPA injectors can be accelerated to high energies while preserving the absolute energy spread (here ≈ 3.84 MeV). This has not been simulated in the present work due to the high computational cost resulting from the symmetric grid resolution required for accurate propagation

of the orthogonal drive and injector pulses. However, our simulations confirm that over the length simulated (0.8 to 1 mm) absolute energy spread and emittance are indeed conserved as the beam accelerates. Using a plasma channel to guide the drive laser pulse after the injector, similar to [13], acceleration to the dephasing length $L_d \approx 2\gamma_p^2 \lambda_p / \pi \approx 16.1$ mm is realistic (well beyond the vacuum laser diffraction length). The maximum energy obtainable can be estimated as $E_{\max} \approx 4\gamma_p^2 e E_x c \omega_p \approx 2.17$ GeV, and hence the potential for relative energy spreads below 1%.

To understand the injection mechanism and the influence of the ionization process, a selection of particle trajectories was traced in the simulations. Figure 2 shows typical trajectories of the trapped (a) preionized and (b) laser-ionized electrons. The background shows the density contour of the wake at $t = 150T_0$. The x coordinates of the curves show the electron positions relative to the head of the laser ($X_e - X_{\text{laserfront}}$). Figure 2 illustrates significant differences between the trajectories of the preionized electrons and the laser-ionized electrons. The longitudinal origin point of the preionized and laser-ionized trajectories are different (the right end of the trajectories), since the preionized electrons are initially in front of the drive pulse and the laser-ionized electrons are born within the laser. From this, we can also see that the trapped laser-ionized electrons are ionized by the driver pulse, not by the colliding pulses.

The initial transverse positions of the preionized electrons are mainly within two transversely separated bands, while the laser-ionized electrons' initial transverse positions appear uniform within a small transverse region (Fig. 2). From additional simulations, we find that the number of bands of preionized electrons can be more than two, and that their transverse positions can be controlled by tuning the relative phase of the two transverse pulses, which is shown in Fig. 2(d). When we change the phase relation between the two pulses, the location of the injection bands move transversely. The transverse position of the bands is near the trough of the standing wave. In this case, only the electrons that pass through these regions can be trapped by the second bucket; other electrons are deflected away due to the strong transverse kick from the standing wave. By retracing the trapped electron trajectories from the standing wave area to the positions in front of the bubble (or wakefield bucket) in the wake rest frame, one finds that the electrons' initial preionized positions will be located in the band regions. However, for the laser-ionized electrons, the situation is different. Trapping may occur even for the electrons initially not within the two bands, since there could be a transverse position shift due to the residual ionization momentum. This can be understood from momentum conservation: the electron momentum after the ionization is $p_y(t) = e[A_y(t) - A_{y\text{ion}}]/c$, where $A_{y\text{ion}}$ represents the laser vector potential at the location

FIG. 2. (a) Trajectories of trapped preionized electrons. The x axis of the trajectories is $X_e - X_{\text{laserfront}}$. The background shows the plasma density after the laser pulse has propagated 0.12 mm. (b) Trajectories of the laser-ionized electrons. (c) Two typical electron trajectories without the colliding pulses (black and green curves) and with the colliding pulses (white and blue curves). The background shows the zoomed wake as shown in (a) and (b). (d) Initial positions of the preionized electrons changing with the initial phase of the transverse colliding pulses. The dashed blue line shows the propagation axis of the two transverse colliding pulses.

where the electron is ionized. The transverse position shift after the drive pulse due to this momentum is approximately $\delta y_{\text{shift}} = \int_{t_{\text{ion}}}^{t_{\text{end}}} p_y / \gamma dt \neq 0$. Ionization can therefore increase the transverse injection area, which then increases the trapped charge.

The standing wave trough selects the trajectories close to the bubble center for both preionized and laser-ionized electrons center, resulting in very small final emittance. In our simulations, the transverse momentum spread of the final accelerated beam can be smaller than 0.04 MeV/ c (see Fig. 3), and the bunch size at the level of $\sim \lambda_0 \sim \mu\text{m}$, and hence the final transverse emittance can be as small as 0.08 mm mrad. In three-dimensional simulations, similar emittances are observed in and out of the plane of the

injection pulse collision (which is also the 2D simulation plane). Emittance in plane is typically $\approx 2/3$ of the out of plane emittance, indicating that three-dimensional effects do not greatly change the injection picture. Due to computational cost, only a few such simulations have been performed to confirm the validity of the two-dimensional scans presented.

Figure 2(d) also shows that the initial longitudinal positions of the trapped preionized electrons are located ahead of the axis of the colliding pulses. These electrons are initially longitudinally pushed forward by the drive pulse and later pass by the drive pulse and then decelerate in the first wake bucket. When the electrons are near the back of the first bucket they interact with the standing wave, pass through the channels created by the standing wave, and finally are trapped in the second bucket. The complete process is shown in Figs. 2(a) and 2(b). Therefore, to increase the injection charge, only the neutral gas ahead of the colliding pulse will contribute.

The simulated parameters are experimentally accessible using state of the art lasers which produce the simulated pulse lengths [29]. The few-lambda foci used has already been used in vacuum, and longer pulses and wider foci can be used at lower plasma densities as it is the ratio of laser dimensions to wake wavelength that is important. Similarly, in the present simulations neutral gas was only used in this region for reasons of computational cost. In an experiment, the results above show that a homogenous mixture could be used with equivalent result. If desired, modulated plasmas for experiments on the 100 μm scale have been demonstrated [30].

In Fig. 2(c) we compared the electron trajectories with and without the transverse pulses. The black and green trajectories are two typical electron trajectories without transverse pulses. The electrons pass the wake buckets and contribute to the background electrons fluid motion. However, with the transverse pulses, the standing wave at the back of the first bucket gives a transverse kick at the same time that the transverse ponderomotive force of the two transverse pulses will kick the electrons along the longitudinal direction of the wake. The particle trajectories have been strongly perturbed and some of electrons are trapped in the second bucket. Two typical trapped trajectories are shown by the white and blue curves in Fig. 2(c). In our simulations we also observe that the longitudinal electric field of the tightly focused transverse pulse is important for the transverse kick. If the two colliding pulse polarizations are initially perpendicular to the simulation box, the trapped number will reduce about 90 percent. This indicates that both the standing wave and the electric field of the colliding pulses contribute to the orbit perturbation. Note that, if the momentum kick is too strong, electrons will be scattered transversely and will not be trapped.

The dependence of the injection process on the laser intensity and nitrogen concentration is shown in Figs. 3(a)

FIG. 3. (a) Electron injection number (stars) and transverse momentum spread (solid circles) versus the transverse laser intensity. (b) Electron injection number (stars) and transverse momentum spread (solid circles) versus the concentration of the neutral nitrogen.

and 3(b). These results indicate that there is an optimal intensity for the transverse pulses. As mentioned above, a transverse pulse with higher intensity will give the electrons a stronger transverse momentum kick, which enhances electron deflection. The standing wave also affects the wake excited by the drive pulse, and if the intensities are too high, the standing wave will suppress electron injection. On the other hand, if the transverse pulse intensity is too low, the electrons will not be trapped. Since the injection area is in a narrow transverse region closed to the axis, the number of trapped preionized electrons is small. To increase the trapped charge, one may use laser ionization as discussed above. Figure 3(b) shows the number of ionized electrons trapped linearly increases with the concentration of the neutral nitrogen. For a large concentration range, the transverse momentum spread remains low. However, when the concentration increases sufficiently, the wake structure will change and the transverse momentum spread increases.

When the two transverse pulses have different frequencies a beat wave with finite phase velocity will be excited instead of a standing wave. This provides a mechanism for transverse asymmetric electron injection. In such a case, the colliding axis should be far away from the density peak, otherwise no electrons will be trapped due to the stronger transverse kick from the beat wave. Here the colliding axis may be placed closer to the drive pulse, and electron

FIG. 4. (a) Plasma density when the drive pulse has propagated 0.55 mm. The black dashed line shows the bubble axis. Injected beams labeled in the dashed square can be seen in the first and second buckets of the wake. The trapped electron bunch centroids are off axis. (b) Distributions of the trapped electrons in P_x - P_y space. The right curve shows the transverse momentum spread and the bottom blue curve shows the longitudinal momentum spread (at 0.55 mm).

injection in the first, as well as the second, bucket occurs. Figure 4(a) shows the injected electron beam after the drive pulse has propagated 0.55 mm. In this case one of the colliding pulse frequencies has been reduced to $\omega/2$. As is evident in Fig. 4(a), at this moment (0.55 mm), the centroid of the injected beam in the first bucket is in the upper-half plane of the wake, and the beam in the second bucket is in the lower-half plane. The electron phase space distributions are shown in Fig. 4(b). The beam has a larger transverse momentum spread and a nonzero centroid value (~ 0.5 MeV/c). These characteristics offer a method to control the cutoff frequency of radiation generated by the electron betatron motion inside the plasma wake [25,31], since both the beam transverse position and momentum can be tuned using the two transverse pulses. The detailed analysis of the radiation generation will be a topic of future work.

In summary, we have proposed and analyzed a method for trapping plasma electrons that results in a beam with controllable transverse momentum spread. This method relies on transverse colliding pulses near the density peak of a laser-driven wakefield. Electrons near the axis are accelerated longitudinally by ponderomotive force of the transverse pulses, accelerated transversely by the beating wave, and subsequently injected into the second bucket of

the wake. Ionization may be used to increase the transverse injection area and the final trapped charge. Simulations show transverse momentum spread can be as small as 0.04 MeV/c and transverse emittance less than 0.1 mm mrad level. Such low emittances are important for many applications, and widen LPA applicability.

These results were presented at the Advanced Accelerator Concepts Workshop, July 10–July 15, 2012 [32]. Subsequently, a transverse colliding pulse scheme for electron beam driven wakefields has been proposed and analyzed [33], in which the ionization process is necessary and dominates the injection. It deserves pointing out that our scheme is workable in laser driven wakefield acceleration which is quite different from Ref. [33]. The scheme there depends on the relatively low intensity of the two transverse colliding pulses since the injection is basically ionization induced injection. However, in our scheme the injection is mostly due to the transverse ponderomotive force acceleration from the colliding pulses and the low emittance is resulting from the channel selection shown in Fig. 2. Ionization can be used to increase the final charge in our scheme, in such a condition, the residual momenta of the injected electrons due to ionization is along the longitudinal direction of the driver pulse. This is the same as the one used in Ref. [33] and was mentioned in our previous publication [32]. It is obvious to see that our scheme is also quite different from the normal colliding pulse injection schemes where the longitudinal acceleration due to the beat wave of the two colliding pulses is used to push the trapped electrons [7]. However, in our scheme the acceleration from the two colliding pulse is transverse to the wakefield. The initial longitudinal acceleration of the trapped electrons is not from the longitudinal force of the beat wave but actually from the transverse ponderomotive force of the two pulses. Under this view, the injection without ionization is more like the scheme described in Ref. [6].

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