Laser and Particle Beams (2009), *27*, 3–7. Printed in the USA.
Copyright © 2009 Cambridge University Press 0263-0346/09 $20.00
doi:10.1017/S0263034609000019

Electron injection into laser wakefields by colliding circularly-polarized laser pulses

W.-M. WANG,[1] Z.-M. SHENG,[1,2,3] AND J. ZHANG[1,2]

[1]Beijing National Laboratory of Condensed Matter Physics, Institute of Physics, CAS, Beijing, China
[2]Department of Physics, Shanghai Jiao Tong University, Shanghai, China
[3]Institute for Fusion Theory and Simulation, Zhejiang University, Hangzhou, China

(Received 14 July 2008; Accepted 29 October 2008)

Abstract

Electron injection into a laser wakefield by the colliding of two circularly polarized laser pulses is analyzed by the Hamiltonian approach and particle-in-cell simulations. If the pump pulse driving the laser wakefield is right-circularly-polarized, electron injection is found only when the counter-propagating injection pulse is left-circularly-polarized and vice versa. This holds when the injection pulse is at low intensity and has a frequency near the pump pulse frequency ω_0. For a moderately intense injection pulse, even if the two pulses have the same polarization, electron injection is found but with less efficiency. It is also found that the injection pulse with the frequency within $[0.5\omega_0,3\omega_0]$ can still create electron injection efficiently provided it has the opposite polarization with the pump pulse.

Keywords: Laser-plasma accelerator; Laser-plasma interaction; Optical injection; PIC simulation

1. INTRODUCTION

Laser-driven plasma acceleration using high-amplitude laser wakefields is promising to make compact accelerators (Tajima & Dawson, 1979). A few recent work demonstrated the generation of quasi-monoenergetic electron beams by an ultra-intense laser pulse (Mangles *et al.*, 2004; 2006; Geddes *et al.*, 2004; Faure *et al.*, 2004; Glinec *et al.*, 2005; Chen *et al.*, 2008). However, the electron injection is basically a nonlinear process, which causes poor reproducibility. How to inject electrons into the acceleration phase of the laser wakefield in a controlled way is crucial. To get this, a few injection schemes have been proposed (Umstadter *et al.*, 1996; Esarey *et al.*, 1997; Fubiani *et al.*, 2004; Kotaki *et al.*, 2004), which use either one or two additional laser pulses to produce electron injection from the background plasma electrons. Umstader *et al.* (1996) first proposed a controlled-injection scheme using an injection pulse propagating orthogonally to the pump pulse and taking the perpendicular polarization of the two pulses. The transverse ponderomotive force, paralleling with the propagation axis of the pump pulse, generated by the injection pulse enables some electrons to deviate from the fluid-oscillation and then be injected. However, a strong injection pulse is needed in this scheme (Hemker *et al.*, 1998; Zhang *et al.*, 2003). Another scheme, proposed by Fubiani *et al.* (2004) and Kotaki *et al.* (2004), uses a counter-propagating injection pulse with the polarization paralleling to that of the pump pulse, which is modified from the scheme proposed by Esarey *et al.* (1997). The injection pulse can significantly change electron trajectories during the overlapping stage of the two pulses and result in the injection of some electrons into the first accelerating bucket of the wakefield. It is found that the required intensity of the injection pulse is much lower than that of the pump pulse. This enables the wakefield structure not to be destroyed and electrons to be stably injected, as shown by simulations (Wang & Sheng, 2008; Sheng *et al.*, 2008) as well as demonstrated by experiments (Faure *et al.*, 2006). Also, there are other schemes (Kaganovich *et al.*, 2005; Lifschitz *et al.*, 2006) proposed to control the electron acceleration.

Up to now, most studies on the colliding injection scheme adopted two linearly polarized pulses. However, the difference between cases of linearly polarized pulses and circularly polarized pulses has not yet been realized, and the impact of the frequency difference on electron injection has not been studied. In this paper, we shall discuss these two points. In the case when both pulses are right-circularly-polarized or

Address correspondence and reprint requests to: Zheng-Ming Sheng, Department of Physics, Shanghai Jiao Tong University, 800 Dongchuan Rd., Shanghai 200240, China. E-mail: zmsheng@sjtu.edu.cn

https://doi.org/10.1017/S0263034609000019 Published online by Cambridge University Press

left-circularly-polarized, their electric field components actually rotate in opposite directions since they counter-propagate. However, when one is right-circularly-polarized and another is left-circularly-polarized, their electric field components rotate in the same direction. This results in significant difference of electron injection. We analyze the electron injection process by the Hamiltonian approach, assuming that the injection pulse is weak enough as not to affect the wakefield excited by the pump pulse. When the rotating directions of the two pulses are opposite, electron injection is not created. While the rotating directions are the same, electron injection can be generated. In this case, efficient injection can be found even if the injection pulse has a frequency much different from the pump pulse.

In Section 2, the Hamiltonian approach is adopted to analyze the dependency of electron injection on the rotating directions of the two circularly-polarized pulses. Then particle-in-cell (PIC) simulations are presented to confirm analytical results. In Section 3, the impact of the injection pulse frequency is discussed by both Hamiltonian analysis and PIC simulations. Finally, a brief summary is given in Section 4.

2. EFFECT OF THE ROTATING DIRECTION OF THE INJECTION PULSE

We consider the interaction of two counter-propagating circularly-polarized pulses in rarefied plasmas, where group velocities of pulses are approximately equal to the vacuum speed of light c. The pump pulse propagates along the $+x$-direction and the injection pulse propagates along the $-x$-direction. We introduce new space and time coordinates $\xi = x - t$, $\tau = t$, where x and t are normalized by the pump pulse wavelength λ_0 and oscillation period T_0, respectively. In one-dimensional (1D) case, it can be assumed that the vector potential $\mathbf{a_1}$ (normalized by mc^2/e) and the wakefield ϕ (normalized by mc^2/e) of the pump pulse are the function of ξ only if there is only the pump pulse. Thus, the Hamiltonian of a test electron is conserved. In order to enable the injection of some background electrons to occur, their Hamiltonians have to be reduced toward the separatrix (Esarey & Pilloff, 1995), which separates open orbits (for untrapped electrons) and closed obits (for trapped electrons), by introducing the injection pulse or other perturbations.

The Hamiltonian with the pump pulse only is given by (Esarey & Pilloff, 1995; Sheng *et al.*, 2000)

$$H^{(0)}(\xi, p_x) = \sqrt{1 + p_x^2 + \mathbf{a}_1^2} - p_x - \phi, \tag{1}$$

where p_x is the axial momentum (normalized by mc). When the injection pulse is much weaker than the pump pulse, one can assume that the perturbation created by the injection pulse only affects the vector potential but not the scalar potential of the wakefield. Then the Hamiltonian with the two pulses is

$$H(\xi, p_x, \tau) = \sqrt{1 + p_x^2 + \mathbf{a}^2} - p_x - \phi, \tag{2}$$

where $\mathbf{a} = \mathbf{a}_1 + \mathbf{a}_2$, and $\mathbf{a}_2$ is the normalized vector potential of the injection pulse. During the overlapping period of the two pulses, electrons will temporarily deviate from the conserved system. But once the perturbation stops, they will return to the conserved system with a new Hamiltonian constant. We assume that an electron starts to be perturbed at τ_1 and stops at τ_2. At τ_1 with $\mathbf{a}_2 = 0$ and its position (ξ_1, p_{x1}) in phase space not changed suddenly, the Hamiltonian is not altered, i.e., $H(\xi_1, p_{x1}, \tau_1) = H^{(0)}(\xi_1, p_{x1})|_{\tau 1}$; At τ_2 when $\mathbf{a}_2 = 0$ again, the Hamiltonian in the conserved system becomes $H^{(0)}(\xi_2, p_{x2})|_{\tau 2} = H(\xi_2, p_{x2}, \tau_2)$. Therefore, the change of the Hamiltonian $\Delta H^{(0)}$ between leaving from and returning to the conserved system is equal to that ΔH during the perturbing period, i.e.,

$$\Delta H^{(0)} = \Delta H = H(\tau_2) - H(\tau_1) = \int_{\tau_1}^{\tau_2} \frac{dH}{d\tau} d\tau. \tag{3}$$

If the Hamiltonian changes of some electrons are negative, the perturbation can be considered to be effective for electron injection. Note the Hamiltonian satisfies that $dH/d\tau = \partial H/\partial\tau = (\mathbf{a}\cdot\partial\mathbf{a}_2/\partial\tau)/\gamma$, where $\gamma = \sqrt{1 + p_x^2 + \mathbf{a}^2}$. Assume the two pulses have the same frequency $\omega_2 = \omega_1 = \omega_0$, the pump pulse is right-circularly-polarized, $\mathbf{a}_1 = a_{10}[\hat{e}_y \cos(2\pi\xi) + \hat{e}_z \sin(2\pi\xi)]$, and the injection pulse is either right or left-circularly-polarized, $\mathbf{a}_2 = a_{20}[\hat{e}_y \cos(2\pi\xi + 4\pi\tau) \pm \hat{e}_z \sin(2\pi\xi + 4\pi\tau)]$ by taking the upper or lower sign, where $a_{20} \ll a_{10}$. Then Eq. (3) is rewritten by

$$\Delta H^{(0)} \simeq \int_{\tau_1}^{\tau_2} \frac{\pm 4\pi a_{10} a_{20} \sin[2\pi\xi \mp (2\pi\xi + 4\pi\tau)]}{\sqrt{1 + p_x^2 + a_{10}^2}} d\tau, \tag{4}$$

taking $\gamma = \sqrt{1 + p_x^2 + \mathbf{a}^2} \simeq \sqrt{1 + p_x^2 + a_{10}^2}$. Since both ξ and p_x are functions of τ, usually Eq. 4 is not easily evaluated. For convenience, one can separate the integral in Eq. (4) into the sum of many integrals within a laser period and analyze the characteristic of the integral in a laser period. Note that under the circularly-polarized pump pulse, the relativistic factor γ varies slowly within a laser period (consider the pulse duration is much larger than T_0). This still holds under the assumption of small perturbations. Therefore, within a laser period, the integral of Eq. (4) is approximately given by

$$\frac{\pm 4\pi a_{10} a_{20}}{\sqrt{1 + p_x^2 + a_{10}^2}} \int_{\tau}^{\tau+1} \sin[2\pi\xi \mp (2\pi\xi + 4\pi\tau)] d\tau. \tag{5}$$

When taking the upper sign in the integrand of term (5) for the two pulses having the same polarization, it reduces to $\sin(4\pi\tau)$, which is a periodic function of τ. Then the integral

https://doi.org/10.1017/S0263034609000019 Published online by Cambridge University Press

(5) is equal to zero. Because this is an integral value within an arbitrary laser period, Eq. (4) vanishes, i.e., $\Delta H^{(0)} = 0$. This indicates that the perturbation generated by the injection pulse at the same polarization with the pump pulse does not lead to effective electron injection.

The lower sign in the integrand of term (5) denotes the opposite polarization of the injection pulse with the pump pulse. In this case, the integrand reduces to $\sin(4\pi\xi + 4\pi\tau)$, and the integral part of term (5) becomes $\int_{\tau}^{\tau+1} \sin(4\pi\xi + 4\pi\tau)\mathrm{d}\tau$. Only when an electron is in-phase with the pump pulse or ξ is constant, the integral is zero always. However, generally ξ varies with τ, which destructs the periodic property, so that the integral has chance to be positive or negative. Thus, after being perturbed, there may be some electrons with sufficient $\Delta H^{(0)} < 0$ for being injected and trapped in the wakefield. This suggests that the perturbation generated by the injection pulse at the opposite polarization with the pump pulse can be effective.

The above results can be understood as follows. The perturbation contributed by the y-direction component of the total vector potential is given by $\int_{\tau}^{\tau+1} \partial/\partial\tau\ [\cos(2\pi\xi)\cos(2\pi\xi + 4\pi\tau)]d\tau = -2\pi\int_{\tau}^{\tau+1} \sin(4\pi\xi + 4\pi\tau)d\tau$. That contributed by the z-direction component is $\pm\int_{\tau}^{\tau+1}\partial/\partial\tau[\sin(2\pi\xi)\sin(2\pi\xi + 4\pi\tau)]d\tau = \pm 2\pi\int\tau^{\tau+1} \sin(4\pi\xi + 4\pi\tau)d\tau$. When the rotating directions of the electric fields of the two pulses are opposite (under the same polarization), the perturbations generated by the y-direction and z-direction components are anti-phased and consequently cancel each other. While the rotating directions of the two pulses are the same, the perturbations produced by the y-direction and z-direction components are in-phase and thereby reinforce each other.

One-dimensional PIC simulations are invoked to check the results presented above. We take an uniform plasma slab with an unperturbed electron density of $0.002n_{cr}$, where $n_{cr} = m\omega_0^2/4\pi e^2$ is the critical density. The pump pulse is fixed with the right-circular-polarization. It has the amplitude $a_{10} = 1.5$ and the width of $20T_0$, and propagates along the $+x$-direction. The injection pulse, either right or left circularly-polarized, has the amplitude $a_{20} = 0.02, 0.2$, and the width of $20T_0$, and propagates along the $-x$-direction. The two pulses with the same frequency (unless stated otherwise) and rectangular profiles, start to overlap at $(x,t) = (95\lambda_0, 955T_0)$, and separate at $(x,t) = (95\lambda_0, 975T_0)$. Without the injection pulse, no electron is injected into the first accelerating bucket of the wakefield at the given conditions.

Figure 1a shows the spatial distributions of laser wakefields during the overlapping period of the two pulses. One can see that the injection pulse either right or left circularly-polarized with $a_{20} = 0.02$ affects the wakefield of the pump pulse quite slightly. The approximation used previously in our Hamiltonian approach applies here. In Figure 1b, one observes that the injection pulse with the left circular-polarization helps to inject electrons into the first acceleration bucket of the wakefield. Whereas, with the injection pulse right-circularly-polarized, no electron is injected into the first bucket, and the electron phase space distribution nearly coincides with that without the injection pulse. These simulation results accord with the above analysis.

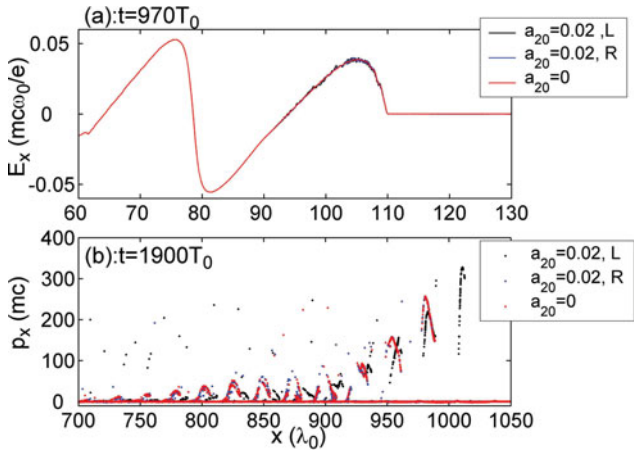


Fig. 1. (**a**) The spatial distributions of laser wakefields, where three lines with different colors denote the injection pulse with the left(L) circular-polarization (black) and the right(R) circular-polarization (blue), and no injection pulse (red), respectively; (**b**) The corresponding phase space distributions of electrons at $t = 1900T_0$.

Further simulations with higher amplitudes of the injection pulse suggest that our analysis given above holds when $a_{20} < 0.05$. However, when $a_{20} \geq 0.05$, the injection pulse with the right circular-polarization can also create electron injection into the first bucket. In this case, the impact of the injection pulse on the wakefield becomes appreciable, and the small perturbation approximation is not valid. Either right circularly-polarized or left circularly-polarized injection pulse can break the conservation of the Hamiltonian system through perturbing the wakefield, and consequently Hamiltonians of some background electrons are possible to be decreased (or some electrons can be preaccelerated). And for the two pulses with opposite polarizations, the perturbations produced, respectively, by the y-direction and z-direction field components should be more coherent than those for the two pulses with same polarization. As a result, the wakefield perturbation for the two pulses with opposite polarizations can be larger and the electron injection can be more efficient, which can be seen in simulations. Figure 2 (with $a_{20} = 0.2$) shows that the injection pulse with the left circular-polarization injects more electrons into the first bucket (see Fig. 2c), introduces larger perturbations of electron motion (see Fig. 2b), and causes stronger destruction on the wakefield (see Fig. 2a) than the right circular-polarized injection pulse. Besides, in the case of left circular-polarized injection pulse, the "beam-loading" effect (Esarey *et al.*, 1997) leads to that the average energy (43 MeV) of trapped electrons in the second bucket is much smaller than that (105 MeV) in the first bucket. The first electron bunch can be picked out using a magnetic field (Umstadter *et al.*, 1996). And energy spread of the first electron bunch is 0.7%.

https://doi.org/10.1017/S0263034609000019 Published online by Cambridge University Press

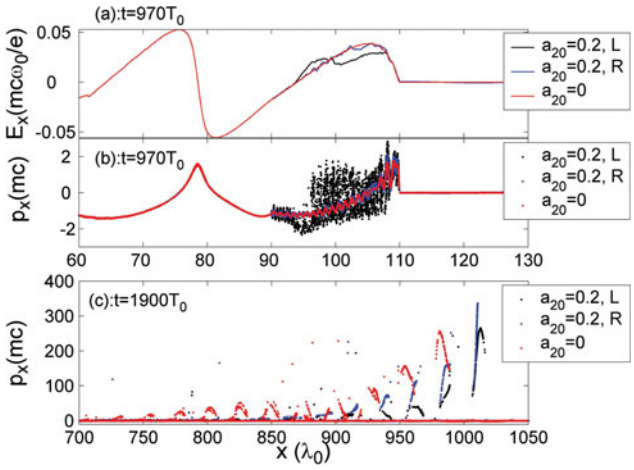


Fig. 2. (**a**) The spatial distributions of laser wakefields, where three lines with different colors denote the injection pulse with the left(L) circular-polarization (black) and the right(R) circular-polarization (blue), and no injection pulse (red), respectively; (**b**) The corresponding phase space distributions of electrons at $t = 970T_0$; (**c**) The corresponding phase space distributions of electrons at $t = 1900T_0$.

3. IMPACT OF THE INJECTION PULSE FREQUENCY

In the following, we shall discuss the impact of the frequency of the injection pulse on electron injection. The form of the pump pulse is not changed and the injection pulse takes the form $\mathbf{a}_2 = a_{20}\{\hat{e}_y \cos[2\pi\omega_2\xi + 4\pi\omega_2\tau] \pm \hat{e}_z \sin[2\pi\omega_2\xi + 4\pi\omega_2\tau]\}$. Then Eq. (4) is rewritten by

$$\Delta H^{(0)} \simeq \int_{\tau_1}^{\tau_2} \frac{\pm 4\pi\omega_2 a_{10} a_{20} sin[2\pi\xi \mp (2\pi\omega_2\xi + 4\pi\omega_2\tau)]}{\sqrt{1 + p_x^2 + a_{10}^2}} d\tau. \quad (6)$$

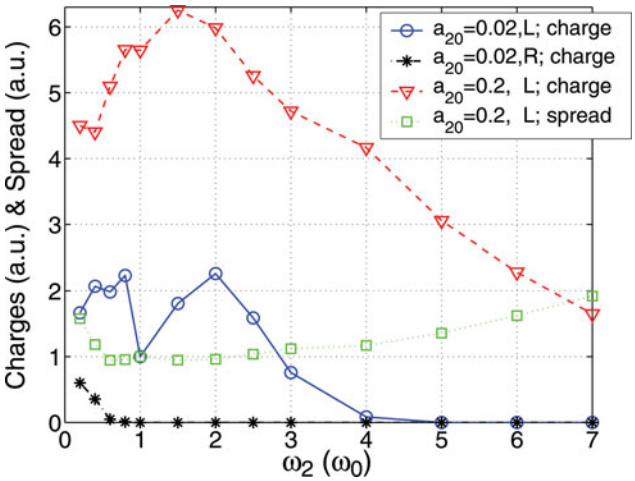


Fig. 3. The injected electron beam charge and energy spread as a function of the injection pulse frequency.

Then the integral of the integrand in Eq. (6) within an arbitrary laser period is approximately given by

$$\frac{-4\pi\omega_2 a_{10} a_{20}}{\sqrt{1 + p_x^2 + a_{10}^2}} \int_{\tau}^{\tau+1} \sin[2\pi(1 + \omega_2)\xi + 4\pi\omega_2\tau] d\tau, \quad (7)$$

$$\frac{4\pi\omega_2 a_{10} a_{20}}{\sqrt{1 + p_x^2 + a_{10}^2}} \int_{\tau}^{\tau+1} \sin[2\pi(1 - \omega_2)\xi - 4\pi\omega_2\tau] d\tau. \quad (8)$$

Terms (7) and (8) denote the cases of the two pulses with different polarizations and the same polarization, respectively. Term (7) can be estimated in a similar way to that of term (5), i.e., electron injection should also be created even if $\omega_2 \neq 1$. The corresponding PIC simulations are shown by the blue solid line in Figure 3 and one can see that the injection pulse with $0.5 \leq \omega_2 \leq 3$ creates electron injection efficiently. Qualitatively, the injection electron number first increases with ω_2, then decreases with it. First, the coefficient ahead of the integral in Eq. (7) is proportional to ω_2. Meanwhile, since the integrand varies with τ faster for a larger ω_2, it can experience more periods within a pump pulse period. Then $\Delta H^{(0)}$, obtained by the sum of more random numbers (positive or negative), inclines to be zero. The competition of the two cases may account for the phenomenon, the number of injected electrons first increases and then decreases with the increasing ω_2 as shown in Figure 3. Increasing a_{20} from 0.02 to 0.2, the charges and energy spread of trapped electron beams are shown by the red broken line and the green dotted line in Figure 3. One sees that the injection pulse with $0.5 \leq \omega_2 \leq 3$ can produce electron injection efficiently and the corresponding energy spread changes slightly.

One can use term (8) to discuss the case of the same polarization. When $\omega_2 \sim 1$, the result should be similar to the case of $\omega_2 = 1$, i.e., almost no electrons are injected. When ω_2 deviates from 1, the varying trend of the injected electron number with ω_2 should be similar to the case of different polarizations. One can see the black dash-dotted line accords with the above analysis.

4. SUMMARY

In conclusion, we have discussed the dependence of electron injection on the polarization and the frequency of the circularly-polarized injection pulse. The injection pulse with the opposite polarization from the pump pulse can generate electron injection more efficiently than the one with the same polarization as the pump pulse. The injection pulse with the frequency different from the pump pulse (e.g., $\omega_2/2 \leq \omega_2 \leq 3\omega_0$) can create electron injection efficiently, too, provided it has the opposite polarization with the pump pulse.

ACKNOWLEDGMENTS

This work was supported in part by the National Natural Science Foundation of China (Grant Nos. 10425416, 10674175,

https://doi.org/10.1017/S0263034609000019 Published online by Cambridge University Press

60621063), the National High-Tech ICF Committee in China, and the National Basic Research Program of China (Grant No. 2007CB815105).

REFERENCES

Chen, Z.L., Unick, C., Vafaei-Najafabadi, N., Tsui, Y.Y., Fedosejevs, R., Naseri, N., Masson-Laborde, P.-E. & Rozmus, W. (2008). Quasi-monoenergetic electron beams generated from 7 TW laser pulses in N2 and He gas targets. *Laser Part. Beams* **26**, 147–155.

Esarey, E. & Pilloff, M. (1995). Trapping and acceleration in nonlinear plasma waves. *Phys. Plasmas* **2**, 1432–1436.

Esarey, E., Hubbard, R.F., Leemans, W P., Ting, A. & Sprangle, P. (1997). Electron injection into plasma wake fields by colliding laser pulses. *Phys. Rev. Lett*. **79**, 2682–2685.

Faure, J., Glinec, Y., Pukhov, A., Kiselev, S., Gordienko, S., Lefebvre, E., Rousseau, J., Burgy, F. & Malka, V. (2004). A laser-plasma accelerator producing monoenergetic electron beams. *Nat*. **431**, 541–544.

Faure, J., Rechatin, C., Norlin, A., Lifschitz, A., Glinec, Y. & Malka, V. (2006). Controlled injection and acceleration of electrons in plasma wakefields by colliding laser pulses. *Nat*. **444**, 737–739.

Fubiani, G., Esarey, E., Schroeder, C.B. & Leemans, W.P. (2004). Beat wave injection of electrons into plasma waves using two interfering laser pulses. *Phys. Rev. E* **70**, 016402.

Geddes, C., Toth, C., Tilborg, J. van, Esarey, E., Schroeder, C., Bruhwiler, D., Nieter, C., Cary, J. & Leemans, W. (2004). High-quality electron beams from a laser wakefield accelerator using plasma-channel guiding. *Nat*. **431**, 538–541.

Glinec, Y., Faure, J., Pukhov, A., Kiselev, S., Gordienko, S., Mercier, B. & Malka, V. (2005). Generation of quasi-monoenergetic electron beams using ultrashort and ultraintense laser pulses. *Laser Part. Beams* **23**, 161–166.

Hemker, R.G., Tzeng, K.-C., Mori, W.B., Clayton, C.E. & Katsouleas, T. (1998). Computer simulations of cathode less, high-brightness electron-beam production by multiple laser beams in plasmas. *Phys. Rev. E* **57**, 5920–5928.

Kaganovich, D., Ting, A., Gordon, D.F., Hubbard, R.F., Jones, T.G., Zigler, A. & Sprangle, P. (2005). First demonstration of a staged all-optical laser wakefield acceleration. *Phys. Plasmas* **12**, 100702.

Kotaki, H., Masuda, S., Kando, M., Koga, J.K. & Nakajima, K. (2004). Head-on injection of a high quality electron beam by the interaction of two laser pulses. *Phys. Plasmas* **11**, 3296–3302.

Lifschitz, A.F., Faure, J., Glinec, Y., Malka, V. & Mora, P. (2006). Proposed scheme for compact GeV laser plasma accelerator. *Laser Part. Beams* **24**, 255–259.

Mangles, S., Murphy, C.D., Najmudin, Z., Thomas, A.G.R., Collier, J.L., Dangor, A.E., Divall, E.J., Foster, P.S., Gallacher, J.G., Hooker, C.J., Jaroszynski, D.A., Langley, A.J., Mori, W.B., Norreys, P.A., Tsung, F.S., Viskup, R., Walton, B.R. & Krushelnick, K. (2004). Monoenergetic beams of relativistic electrons from intense laser-plasma interactions. *Nat*. **431**, 535–538.

Mangles, S.P.D., Walton, B.R., Najmudin, Z., Dangor, A.E., Krushelnick, K., Malka, V., Manclossi, M., Lopes, N., Carias, C., Mendes, G. & Dorchies, F. (2006). Table-top laser-plasma acceleration as an electron radiography source. Laser Part. *Beams* **24**, 185–190.

Sheng, Z.-M., Sentoku, Y., Mima, K., Zhang, J., Yu, W. & Meyer-ter-Vehn, J. (2000). Angular distributions of fast electrons, ions, and bremsstrahlung X/G-rays in intense laser interaction with solid targets. *Phys. Rev. Lett*. **85**, 5340–5343.

Sheng, Z.-M., Wang, W.-M., Trines, R., Norreys, P., Chen, M. & Zhang, J. (2009). Mechanisms of electron injection into laser wakefields by a weak counter-propagating pulse. *Euro. Phys. J*. In Press.

Tajima, T. & Dawson, J.M. (1979). Laser electron accelerator. *Phys. Rev. Lett*. **43**, 267–270.

Umstadter, D., Kim, J.K. & Dodd, E. (1996). Laser injection of ultrashort electron pulses into wakefield plasma waves. *Phys. Rev. Lett*. **76**, 2073–2076.

Wang, W.-M. & Sheng, Z.-M. (2008). Effect of laser parameters on electron injection into laser wakefields in plasma with a counter propagating additional laser pulse. *Phys. Plasmas* **15**, 013101.

Zhang, P., Saleh, N., Chen, S.Y., Sheng, Z.M. & Umstadter, D. (2003). An optical trap for relativistic plasma. *Phys. Plasmas* **10**, 2093–2099.

https://doi.org/10.1017/S0263034609000019 Published online by Cambridge University Press