Electron Optical Injection with Head-On and Countercrossing Colliding Laser Pulses

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A high stability electron bunch is generated by laser wakefield acceleration with the help of a colliding laser pulse. The wakefield is generated by a laser pulse; the second laser pulse collides with the first pulse at 180° and at 135° realizing optical injection of an electron bunch. The electron bunch has high stability and high reproducibility compared with single pulse electron generation. In the case of 180° collision, special measures have been taken to prevent damage. In the case of 135° collision, since the second pulse is countercrossing, it cannot damage the laser system.

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Laser wakefield acceleration (LWFA) [1], based on the effect of plasma waves excitation in the wake of an intense laser pulse, is now regarded as a basis for the next generation of charged particle accelerators. Electron bunches have been accelerated up to 1 GeV by LWFA [2]. In experiments, it has been demonstrated that LWFA is capable of generating electron bunches with high quality [3,4].

In order to generate a bunch with high quality, required for applications, the electrons should be duly injected into the wakefield and this injection should be controllable. The injection can happen spontaneously, due to a longitudinal or transverse break of the wake wave, caused by its strong nonlinearity [5] and with cluster-gas targets [6]. This regime leads to the acceleration of fast particles, although in an uncontrolled way. Several other schemes of the electron injection were proposed to provide more controllable regimes including tailored plasma density profiles [7] and the so-called optical injection [8–12]. Within the optical injection, the electrons are injected into the wakefield by the additional laser pulse. Optical injection has an advantage in using a regular pattern wakefield. In the regime below the wave breaking [13], the wakefield parameters are reproducible from shot to shot with less sensitivity to plasma fluctuations in this regime than self-injection. The optical-injection scheme has the potential for the stable and controllable generation of electron bunches. The most simple optical-injection scheme is based on the utilization of two counterpropagating laser pulses [10,11]. In the case of the collision of two counterpropagating laser pulses, the driver pulse generates the wakefield in a plasma, and the injecting pulse colliding with the driver pulse provides the conditions for the electron trapping by the wake wave.

In this Letter we present the exprimental and simulation results of the optical-injection studies from the collisions of laser pulses in head-on and countercrossing configurations at the angle of 135°. At first, we present the result of the head-on configuration.

The experiments have been performed with a 11 TW linearly polarized Ti:sapphire laser [14]. The 40 fs driver pulse with 0.4 J energy is focused onto a 1-mm-diameter helium gas jet by an off-axis parabolic mirror (OAP). The peak irradiance, $I_0 = 3.0 \times 10^{18}$ W/cm^2, corresponds to a dimensionless amplitude of the laser field $a_0 = eE_0/(mc^2k) = 8.5 \times 10^{-10} \lambda_0[\mu\mathrm{m}]\sqrt{I_0[\mathrm{W/cm}^2]} = 1.2$, where λ_0 is the laser light wavelength of 800 nm. The 50 fs injecting pulse with 30 mJ energy is focused onto the focus point of the driver pulse by an OAP at the angle of 180°. Its peak irradiance, I_1, is about 8.0×10^{16} W/cm^2, corresponding to a dimensionless amplitude of $a_1 = 0.2$. In order to register the accelerated electron bunch, we use an electron spectrometer, consisting of a permanent magnet and a charge-coupled device (CCD) camera.

In order to demonstrate the optical injection, we must use plasma with a density below the self-injection threshold. When the plasma density, n_e, is 2.00×10^{19} cm^{-3}, the reproducibility of the electron beam generation is 100% (not stable in beam quality). At $n_e = 1.00 \times 10^{19}$ cm^{-3}, the reproducibility drops to 0%. This density is below the wave-breaking threshold where the self-injection is reliably ceased. Figure 1 shows the result of the optical injection for $n_e = 1.00 \times 10^{19}$ cm^{-3}. The collision of the two laser pulses produces a monoenergetic electron bunch with the energy of about 134 MeV and a 3.5% root-mean-square (rms) energy spread. Using the sensitivity of the phosphor screen, calibrated with the help of a conventional electron accelerator, we estimate that the total charge of the monoenergetic electron bunch is 8.7 pC. Taking the size of the electron bunch image on the phosphor screen, we find the electron bunch divergence, $\theta_e =$ 4 mrad.

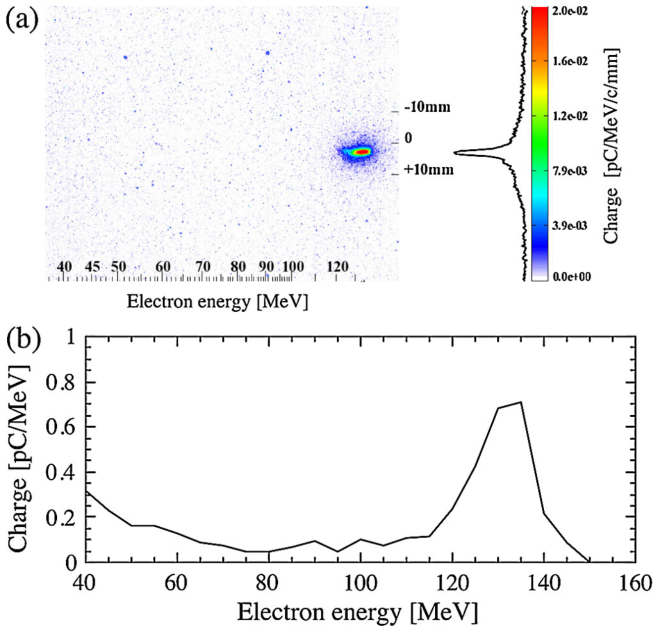

FIG. 1 (color online). A typical image of an energy distribution of the electron bunch at $n_e = 1.00 \times 10^{19}$ cm^{-3} with the injecting laser pulse at the angle of 180° (a), and a projection of the image onto the energy axis (b). The monoenergetic electron bunch has a peak energy of 134 MeV and an energy spread of 3.5%.

In the head-on collision of two laser pulses the backward propagating radiation must be absorbed or shielded before it enters the laser system to prevent its damage. Another complication is in the arrangement for the high energy electron bunch usage, since fast electrons propagate in the same direction as the propagation of the two laser pulses. Below we present the first demonstration of the optical injection in the countercrossing configuration. The counterpropagating collision of two laser pulses has been realized in the experiments presented in Ref. [12].

For countercrossing, the experiments have been performed with a 2 TW linearly polarized Ti:sapphire laser [15]. The target is a supersonic helium gas jet flowing out of a rectangular nozzle with the size of 1.3 mm $\times$ 4 mm. The density fluctuation is less than $\pm 10^{17}$ cm^{-3} when we hold constant the stagnation pressure to the gas-jet valve. The 70 fs driver pulse with 0.2 J energy is focused onto the helium gas jet. The peak irradiance, I_0, is 6.8×10^{17} W/cm^2 corresponding to a dimensionless amplitude of $a_0 = 0.6$. The 70 fs injecting pulse with 10 mJ energy is focused onto a region at the beginning of a channel formed by the driver pulse at the angle of 135° with respect to the driver pulse propagation. Its peak irradiance I_1 is about 2.0×10^{16} W/cm^2, corresponding to a dimensionless amplitude of $a_1 = 0.1$. We performed a theoretical estimation to determine the driver pulse amplitude. According to theoretical estimation and simulation, the driver pulse amplitude becomes equal to 1.0 due to self-focusing [16]. For the estimations see Ref. [17]. The power of the injecting pulse is smaller than the threshold for relativistic self-

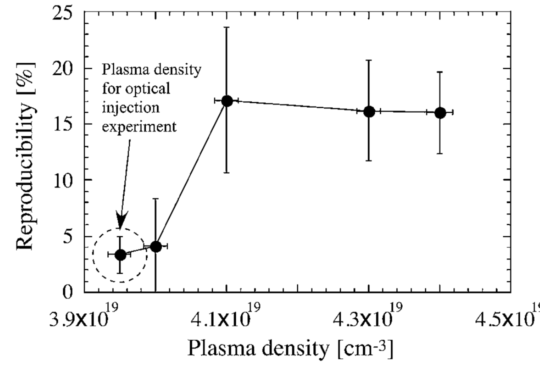

FIG. 2. Reproducibility of the self-injected quasimonoenergetic electron beam. The vertical bars show the standard deviation. The horizontal bars show the fluctuations of the plasma density. The reproducibility suddenly rises from 4% to 16% between $n_e = 4.00 \times 10^{19}$ cm^{-3} and 4.10×10^{19} cm^{-3}. The reproducibility is 3.3% at $n_e = 3.95 \times 10^{19}$ cm^{-3}, because the plasma density is below the threshold density.

focusing, $P_c = 16.2(\omega/\omega_p)^2$ GW, where ω_p is the plasma frequency. However, the measured spot size of the injecting pulse in plasma becomes smaller than in vacuum, and a_1 is expected to be equal to 0.3. The injecting pulse may be also focused due to the plasma density distribution, the refractive index in plasma and gas, and the front shape of the plasma ionized by the driver pulse.

The self-injection ceases at lower plasma densities, when the wake wave becomes more regular. In order to demonstrate the countercrossing injection, we must use plasma with a density below the self-injection threshold. The threshold parameters are found by changing the plasma density and measuring accelerated electrons with

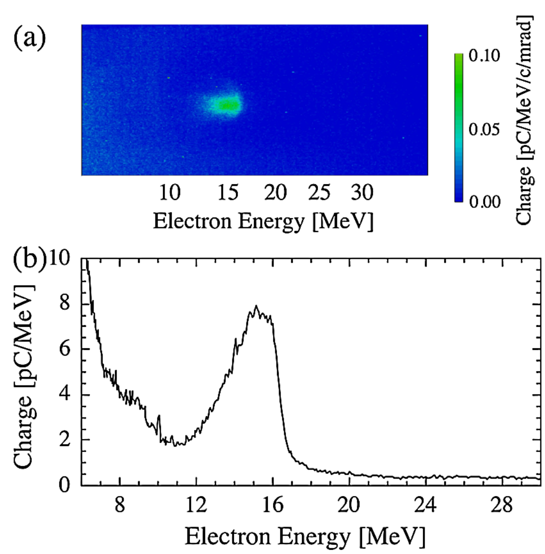

FIG. 3 (color online). A typical image of an energy distribution of the electron bunch obtained by the countercrossing injection at $n_e = 3.95 \times 10^{19}$ cm^{-3} (a), and a projection of the image onto the energy axis (b). The quasimonoenergetic electron bunch has a peak energy of 15 MeV and an energy spread of 7.8%.

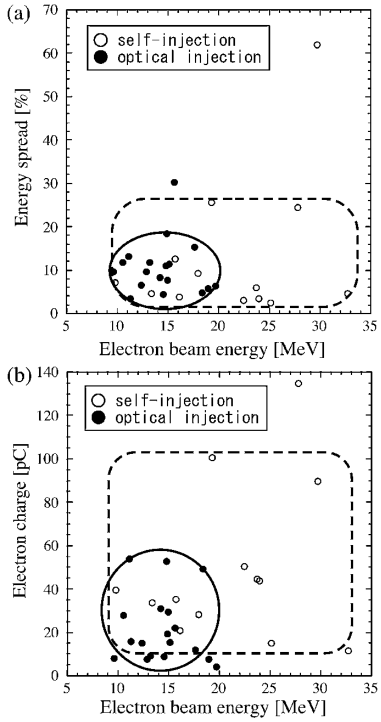

FIG. 4. The stability of the self-injection and the countercrossing injection. The stability of the countercrossing injection is higher than that of the self-injection.

the driver pulse alone as shown in Fig. 2. The reproducibility is the percentage to generate a quasimonoenergetic electron beam. The electron bunch acceleration occurs in the self-modulated laser wakefield acceleration regime [4,18]. When the plasma density decreases from 4.10×10^{19} cm^{-3} to $n_e = 4.00 \times 10^{19}$ cm^{-3}, the reproducibility abruptly drops. For our parameters, the self-injection ceases at the plasma density below the threshold of 4.00×10^{19} cm^{-3}.

Figure 3 shows the energy spectrum of the accelerated electron bunch optically injected with the help of the injecting pulse for $n_e = 3.95 \times 10^{19}$ cm^{-3}. This density is below the self-injection threshold. The collision of the two laser pulses produces a quasimonoenergetic electron bunch with 15 MeV peak energy, 7.8% (1.2 MeV) rms energy spread, 30 pC charge, and 15 mrad divergence. We observed the quasimonoenergetic electron bunches in 18 of 38 shots; i.e., with the reproducibility equal to 50%. The mean parameters of the electron beams and their standard deviations for the countercrossing injection correspond to the electron beam peak energy of 14.4 ± 0.7 MeV, the rms energy spread of $10.6 \pm 1.5\%$ (1.5 ± 0.2 MeV), and the electron charge of 21.8 ± 3.8 pC.

Figure 4 compares the stability of the self-injection and the countercrossing injection mechanism. The experiments of the countercrossing injection were conducted for $n_e = 3.95 \times 10^{19}$ cm^{-3}. The self-injection has been seen for $n_e = 4.40 \times 10^{19}$ cm^{-3}. These results show that the countercrossing injection has higher stability than the self-injection. Figure 4 shows a wide scatter of the self-injection points, with several at large values, while the optical-injection points are clustered nearer to the lower left of each plot.

In order to elucidate the electron injection in the case of the countercrossing interaction of two laser pulses, we performed two-dimensional (2D) particle-in-cell (PIC) simulations by using the REMP code [19]. The simulations presented here are for linearly polarized laser pulses with the dimensionless amplitudes $a_0 = 1.0$ and $a_1 = 0.3$. The laser pulses have a Gaussian envelope. The laser pulse width is $\tau = 70$ fs. The plasma density is $n_e = 4.0 \times 10^{19}$ cm^{-3}. The simulation parameters are close to the parameters of our experiment. In Fig. 5 we present the simulation result. We see the self-modulation regime in the laser pulse evolution. The wave breaking produces only a few electrons and a broad energy spectrum. In the case of $\tau = 70$ fs and $n_e = 4.0 \times 10^{19}$ cm^{-3}, plasma electrons are injected into two buckets of the acceleration phase by the collision of the driver and injecting pulse, because the interaction length of the laser pulses are larger than the plasma period.

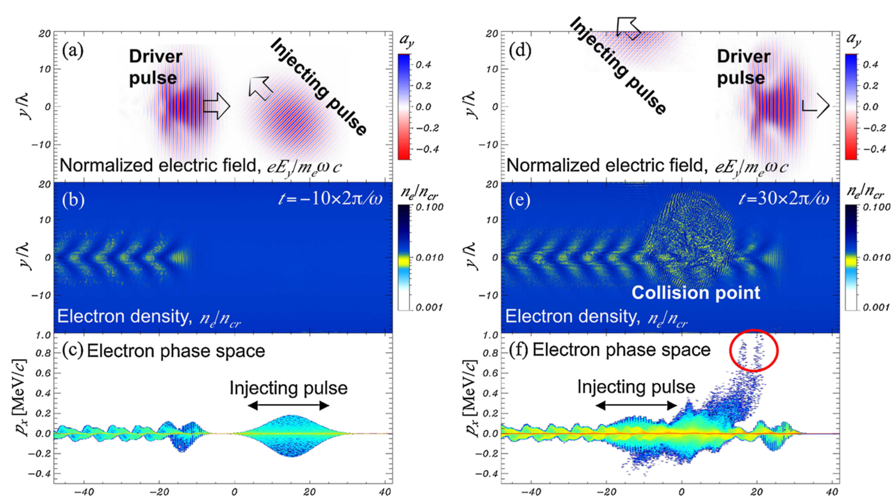

FIG. 5 (color online). 2D PIC simulation result for $a_0 = 1$ and $a_1 = 0.3$. (a), (d) Normalized electric field component a_y, (b),(e) electron density n_e, and (c),(f) electron phase space projection onto the (x, p_x) plane before and after the pulses countercrossing, at $t = -10$ (a),(b),(c), and at $t = +30$ (d),(e),(f). Time unit is the laser period. Injected electrons are marked in (f) by the red circle. Note the wake wave persistent distortion at the location of countercrossing and restoration of the wake wave after collision of the pulses.

TABLE I. Optically injected electron beams for each angle. (a) A driver pulse collides with an injecting pulse without a plasma wave (180° collision). (b) A driver pulse collides with an injecting pulse at the point of a plasma wave (135° collision). (c) A driver pulse collides with a plasma wave without an injecting pulse (90°). ○ indicates that there is a quasimonoenergetic electron beam. × indicates that there is no quasimonoenergetic electron beam or high energy electrons.

n_e [cm^{-3}]	(a)	(b)	(c)
(1.6–1.9) $\times 10^{19}$	○	○	×
1.5×10^{19}	×	○	×
1.4×10^{19}	×	×	×

For the 135° collision case, we need to consider a colliding pulse injection (head-on collision) [10,11] with an optical trap (90° collision) [9]. The effect of the optical trap changes the plasma density at the collision point. In order to consider it separately from the colliding pulse effect, we performed 1D-PIC simulations for $\tau = 70$ fs at $a_0 = 1.0$ and $a_1 = 0.3$. The optical trap effect was added as a plasma wave at the collision point. At first, we performed the density scan for self-injection the same as the experiment. Below $n_e = 1.9 \times 10^{19}$ cm^{-3}, no electrons are accelerated. Below $n_e = 1.9 \times 10^{19}$ cm^{-3}, we performed the simulation (a) with the injecting pulse and without the plasma wave (180° collision), (b) with the injecting pulse and the plasma wave (135° collision), and (c) without the injecting pulse and with the plasma wave (90° collision). Table I shows the results. For $n_e =$ (1.6–1.9) $\times 10^{19}$ cm^{-3}, the energy spectrum of the 135° collision is similar to that of the 180° collision. For $n_e = 1.5 \times 10^{19}$ cm^{-3}, however, only the 135° collision has an accelerated electron beam. The optical trap effect is smaller than the effect of the head-on collision. However, the optical trap effect is not zero. The result shows that the mechanism of the countercrossing injection is the combination of the colliding pulse injection [10,11] and the optical trap [9].

In conclusion, we conduct two optical-injection experiments. The first one is a 180° collision, $a_0 = 1.2$, $a_1 = 0.2$, and $\tau = 40$ fs. The second one is a 135° collision, $a_0 = 1.0$, $a_1 = 0.3$, and $\tau = 70$ fs. The a_0 for the first experiment is bigger than for the second experiment. The electron beam energy of the first experiment is higher than that of the second experiment. The a_1 for the first experiment is 0.2, and for the second experiment is 0.3. The charge of the injected electron bunch drops between $a_1 = 0.3$ and 0.2 [10]. In addition, the pulse width for the second experiment is longer than it for the first experiment. So, the electron beam charge of the second experiment is bigger than that of the second experiment. Quasimonoenergetic electron bunches are obtained by colliding two countercrossing pulses. The mechanism of the optical injection is the combination of the colliding pulse injection and the optical trap. The advantage of the countercrossing configuration is that the injecting pulse cannot damage the laser system and that the arrangement for electron bunch applications and measurement are simpler than in the case of the counterpropagating configuration. We demonstrated that the stability and the reproducibility of the electron injection are significantly higher in the case of the countercrossing optical injection than in the case of self-injection.

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