Counter-Crossing Injection for Stable High-Quality Electron Beam Generation via Laser-Plasma Interaction

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Abstract. Counter-crossing injection, which is a realistic setup for applications, by two sub-relativistic laser pulses colliding at an angle of 45 degrees is demonstrated. The collision of the two laser pulses generates a high-quality electron beam with high reproducibility. The generated monoenergetic electron beam has a peak energy of 14.4 MeV, an energy spread of 10.6%, a charge of 21.8 pC, a normalized emittance of 1.6 mm mrad, and a reproducibility of 50%. The electron beam generation is unfolded with two-dimensional-particle-in-cell simulations. The laser pulses in plasma are self-focused to higher intensity when the laser power is above the threshold for relativistic self-focusing. The collision of the self-focused laser pulses generates a high-quality electron beam with high reproducibility.

1. Introduction

Laser-driven plasma accelerators, based on using the wakefield, are conceived to be the next-generation particle accelerators, promising ultrahigh field particle acceleration and compact size compared with conventional accelerators [1]. Laser acceleration can generate an electron beam which is quasi-monoenergetic, low in emittance, and ultrashort [2-7]. The electron beam generation, however, is not of high reproducibility. From the viewpoint of applications, which require high-quality electron beams with small momentum spread and good pulse-to-pulse parameter reproducibility, it is crucial that an ultrashort particle bunch with an energy higher than the trapping threshold be consistently injected into the acceleration phase of the wakefield. The optical injection method [8-15], which utilizes multiple laser pulses, can stably generate electron beams, because a good quality wake wave for electron acceleration can be used within the framework of this scheme. The optical injection mechanism also provides a controlled condition for the electron beam generation, because the trapping of the plasma electrons into the plasma wake and the acceleration of the electron bunch are performed independently of each other [8-15], like in a conventional radio-frequency (rf) accelerator. In order to generate a stable high-quality electron beam in a simpler way, counter propagating two laser pulse collision type optical injection has been proposed [14, 15]. Recently, controlled injection based on this
approach was demonstrated experimentally [16]. In the case of the collision of two counter-propagating laser pulses, the first laser pulse (the driver pulse) creates a wakefield, and the second laser pulse (the injecting pulse) injects electrons by colliding with the driver pulse. The previous experiment [16] was carried out in the head-on collision configuration. The head-on collision leads to the unavoidable backward propagation of laser light into the laser system and the lack of an exit for the electron beam generated on the laser axis for applications.

In this paper, we present the results of the counter-crossing electron injection by two laser pulses in the Self-Modulated Laser WakeField Acceleration (SM-LWFA) regime [17, 18]. In SM-LWFA we use a relatively high plasma density and long pulse. The colliding angle is chosen to be 45 degrees in order to avoid backward propagating laser light and to open up the electron beam line for various applications. In Sec. II, we present an experimental setup and conditions. In Sec. III, we present the experimental results. In Sec. IV, we present two-dimensional (2D) -particle-in-cell (PIC) simulation results. Sec V contains conclusions.

2. Experimental setup and condition

The experiments are performed with a 10 Hz Ti:sapphire laser system. Figure 1 shows the experimental setup of the counter-crossing injection. The nozzle for a supersonic helium gas jet has a rectangular shape of 1.3 mm × 4 mm.

The 70 fs driver pulse with 212 mJ pulse energy is focused in the helium gas jet by using a 646 mm focal length, f/13 off-axis parabolic mirror. The spot radius in vacuum at the focus, \(w_0\), is 12.5 \(\mu\)m at \(1/e^2\). The energy concentration is 55% within the \(1/e^2\) spot. The focal peak irradiance, \(I_0\), is estimated to be \(6.8 \times 10^{17}\) W/cm\(^2\). This corresponds to a dimensionless amplitude of the driver laser field, \(a_0\), equal to 0.6, where \(a_0 = 8.5 \times 10^{-10} \lambda_0^2/\sqrt{I_0}\), \(\lambda_0\) is the laser light wavelength, \(I_0\) is the irradiance.

The 70 fs injecting pulse with 10 mJ pulse energy is focused at the starting point of the driver pulse channel with the angle of 45 degrees by using a 200 mm focal length, f/4 convex lens. The spot radius in vacuum at the focus, \(w_1\), is 15 \(\mu\)m at \(1/e^2\). The energy concentration is 50% within the \(1/e^2\) spot. The focal peak irradiance, \(I_1\), is estimated to be \(2.0 \times 10^{16}\) W/cm\(^2\). This corresponds to a dimensionless amplitude of the injecting laser field, \(a_1\), equal to 0.1.

In order to detect the energetic electron spectrum, we use an electron spectrometer. The electron signal is monitored by a DRZ phosphor screen and a CCD camera. The electron beam path from the gas jet center to the DRZ screen center is about 350 mm.

Figure 1. Experimental setup for the counter-crossing injection. The driver pulse and the injecting pulse are focused onto the helium gas jet with the collision angle of 45 degrees.

3. Experimental results

For our laser pulse, we can suppress the self-injected electron beam below the plasma density, \(n_e\), of \(n_e = 4.00 \times 10^{19}\) cm\(^{-3}\). Figure 2 shows the energy spectrum of the generated electron beam by the counter-crossing injection results at \(n_e = 3.95 \times 10^{19}\) cm\(^{-3}\), which is below the threshold of \(n_e = 4.00 \times 10^{19}\) cm\(^{-3}\). The collision of the two laser pulses produces a monoenergetic electron beam around 15 MeV with a 7.8% (1.2 MeV) energy spread. By using the sensitivity of the DRZ screen, the total charge of the monoenergetic electron beam is found to be 30 pC. The image spatial size at the DRZ screen in the vertical direction is 5.4 mm (rms). We find the electron
beam divergence, $\theta_e$, to be about 15 mrad. The normalized emittance of the electron beam, $\varepsilon_n$, is obtained by $\varepsilon_n = \gamma e r_e \theta_e$, where $\gamma$ is the Lorentz factor of the energy of the electron beam, $r_e$ is the rms size of the electron beam at the laser focus point, and $\theta_e$ is the rms divergence angle. Assuming the electron beam size is equal to half of the laser spot size, because the driver laser pulse is self-focused in the plasma and the electron beam is inside the wake wave excited by the driver pulse, we find $\varepsilon_n$ to be at most $1.4\pi$ mm mrad.

We scan the delay between the two laser pulses. The electron beam can be generated within a delay of 100 fs. This shows that the two laser pulse collision strongly affects the electron beam generation. Within the delay time, the reproducibility of the monoenergetic electron beam generation is about 50%. Table 1 summarizes the mean parameters of the electron beams and their standard deviations. These results show that the counter-crossing injection has higher stability and higher reproducibility than the self-injection.

![Figure 2. A typical energy distribution of the electron beam obtained by the counter-crossing injection. The monoenergetic electron beam at $n_e = 3.95 \times 10^{19}$ cm$^{-3}$ has a peak energy of 15 MeV and an energy spread of 7.8%.](image)

| Table 1. Monoenergetic electron beams generated by the counter-crossing injection at $n_e = 3.95 \times 10^{19}$ cm$^{-3}$ and the self-injection at $n_e = 4.40 \times 10^{19}$ cm$^{-3}$ (near the optimum density). |
|-----------------------------------------------------------|
| **Peak energy [MeV] (mean $\pm$ s.d.)**                  | counter-crossing injection | self-injection       |
|-----------------------------------------------------------|
| Energy spread [%] (mean $\pm$ s.d.)                      | 14.4 $\pm$ 0.7             | 21.3 $\pm$ 1.9       |
| Charge [pC] (mean $\pm$ s.d.)                            | 10.6 $\pm$ 1.5             | 13.1 $\pm$ 4.6       |
| Reproducibility [%]                                     | 21.8 $\pm$ 3.8             | 50.0 $\pm$ 10.1      |
|-----------------------------------------------------------|

![Figure 3. 2D PIC simulation result for $a_0 = 1$ and $a_1 = 0.3$. Electric field component, $E_y$, electron density, $n_e$, and electron phase space projection onto the $(x, p_x)$-plane after the pulses counter-cross at $t = +30$. The time unit is the laser period. Injected electrons are marked by the circle. Note the wake wave persistent distortion at the location of counter-crossing and restoration of the wake wave after collision of the pulses.](image)
4. 2D-PIC simulation

In order to elucidate the electron beam mechanism by the counter-crossing injection with sub-relativistic intensity laser pulses, 2D-PIC simulations with the moving window technique are performed with the use of the REMP code [19]. The simulations presented here are for linearly p-polarized laser pulses with the dimensionless amplitudes $a_0 = 1.0$ and $a_1 = 0.3$. These amplitudes are the expected parameters after relativistic self-focusing in plasma [20, 21]. The laser pulses have a Gaussian envelope. The plasma density is $n_e = 4 \times 10^{19}$ cm$^{-3}$. These initial parameters are close to the experimental parameters. In Fig. 3 we present the 2D-PIC simulation result. We see the SM regime of the laser pulse evolution. At this density and laser pulse parameters the wave breaking gives only few electrons and a wide spectrum. Plasma electrons are injected into the acceleration phase by collision of the driver and the injecting pulse. The simulation result shows that the counter-crossing pulses can inject plasma electrons into the plasma wake. The injected electrons are accelerated by the wake toward high energy.

5. Conclusions

Monoenergetic electron beams are observed by colliding two 70 fs sub-relativistic laser pulses. The collision of the self-focused laser pulses injects a part of the plasma electrons into the wakefield excited by the driver pulse. The wakefield accelerates the injected electrons to high energy. The 2D-PIC simulation result also shows the electron beam generation via the counter-crossing injection. The reproducibility of the electron beam generation is about 50%. The electron beam generated by this optical injection will lead to various applications.

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