Generation of a high quality electron beam by the colliding two laser pulses

Hideyuki KOTAKI, Masaki KANDO, Shin-ichi MASUDA, Shuji KONDO, Shuhei KANAZAWA, Takayuki HOMMA, and Kazuhisa NAKAJIMA

Japan Atomic Energy Research Institute,Kizu, Kyoto, 619-0215, Japan

Abstract

We investigate generation of electron beams injected by the interaction of two laser pulses. A single laser pulse produces an electric field (wakefield). By using two laser pulses electrons can be injected from the plasma into the wakefield. We term the scheme "colliding pulse optical acceleration". We perform theoretical analysis and numerical simulation of the colliding pulse optical acceleration by two laser pulses. The accelerated electron beam has a small energy spread and ultrashort pulse duration. Also, the electron beam has an emittance lower than the best quality beam produced by conventional RF accelerator technology. We find that a high quality intense relativistic electron beam is generated.

Introduction

Electron beam injection triggered by an intense ultrashort laser has been proposed as an injector of ultrashort electron beams referred to as "optical injection". Presently there are three major schemes: nonlinear wave-breaking injection[1], transverse optical injection[2], and colliding pulse optical injection[3][4][5]. Three laser pulses consisting of a pump pulse for wakefield excitation and two injection pulses for trapping the electrons from the plasma make up the colliding pulse optical injector. The colliding pulse optical injection is a high quality optical injector. The optical injection, however, is the most difficult.

The counter-propagate laser pulses inject electrons from the plasma into a wakefield excited by one of the laser pulses. One of the laser pulses injects and accelerates electrons. We call the mechanism "colliding pulse optical acceleration". The experiment of the colliding pulse optical acceleration is easier than the colliding pulse optical injection, and has the possibility to become a high quality electron injector similar to colliding pulse optical injection. We present optical injection and acceleration schemes that utilize two counter-propagating laser pulses.

Colliding 2 laser pulses

Two counter-propagating laser pulses each produce plasma waves. The interaction of pulse 0 and pulse 1 generates a standing wave. We assume the electric field **E** is

$$\mathbf{E} = \mathbf{E}_0\cos(k_0z-\omega_0t)+\mathbf{E}_1\cos(k_0z+\omega_0t),$$

where ω_0 and k_0 are the frequency and the wave number of the laser, and E_0 and E_1 are electric field of the laser pulses. The momentum p_{inj} of the injection is obtained

$$p_{inj} = \gamma_{inj}m_ec = CE_0E_1[\sin(2\omega_0t)-2\omega_0t\cos(2k_0z)],$$

where γ_{inj} is the normalized energy of injection and C is $e^2/2m_e\omega_0^3$. This equation shows that electrons in the plasma are accelerated from oscillations generated by the colliding laser pulses. Electrons in the plasma are injected into the wakefield, when the laser pulses collide and the laser strength parameter is above the trapping threshold. For the laser strength parameters a_0 of 1.0 and a_1 of 0.4, the rms electron pulse duration τ_e(rms) is written by

$$\tau_e(\mathrm{rms}) = 0.10\,\tau_L(\mathrm{FWHM}),$$

where τ_L(FWHM) is the full width at half maximum pulse width of the laser pulse. The electron bunch compression effect is included in the pulse duration.

Simulation results of the optical injection

In order to estimate the quality of the generated electron beam, we performed 1-D Particle-in-Cell (PIC) simulations[6] for the colliding pulse optical acceleration in the linear regime. The length of the simulations is 1 mm, and the colliding point of two laser pulses is at the center. A portion of the electrons in the plasma is trapped and accelerated to high energy by the wakefield excited by the pump pulse. The accelerated electron beam is clearly separated from electrons in the plasma.

The electron beam at $n_e=7\times10^{17}\mathrm{cm}^{-3}$ for a_0=1.0 and a_1=0.4 has a pulse duration of 7.4 fs (rms) and a charge of 31 pC corresponding to the peak current of 1.5 kA. It would be difficult to generate such an ultrashort intense electron beam with conventional RF accelerators. Figure 1 shows the pulse duration of the injected and accelerated electron beam. The dotted lines show the theoretical value at λ_p[mm]=0.8τ_L(FWHM)[fs]. The simulation results are consistent with the theoretical values. The electron bunch injected into the wakefield excited by the pulse 0 is also compressed and stretched in the field before becoming relativistic. The pulse duration of the accelerated electron beam changes after trapping into the wakefield which works as a compressor and a stretcher not only an accelerator.

Figure 2 shows the accelerated electrons energy at $n_e=7\times10^{17}\mathrm{cm}^{-3}$ for a_0=1 and a_1=0.4. The accelerated energies are consistent with linear theory and the energy spread is very small. The energy and the energy spread are 9.5 MeV and 1.42%, respectively.

For the quality of the electron beam, the emittance is one important parameter. Figure 3 shows the distribution of the transverse normalized velocities β_t of the accelerated electrons at $n_e=7\times10^{17}\mathrm{cm}^{-3}$ for a_0=1.0 and a_1=0.4. We can obtain an emittance of the electron beam from β_t = 0.0029. The normalized emittance ε_{nx} of the electron beam is approximately,

$$\varepsilon_{nx} = \rho_e \gamma \beta \beta_t,$$

where r_e is the electron beam radius, γ is the normalized energy, and β is the longitudinal normalized velocity of the electron. For the electron energy of 9.5 MeV, γ and β are approximately equal to 18.6 and 1, respectively. Assuming the electron beam radius, r_e=15mm, the normalized emittance of the accelerated electrons is 0.3 π mm mrad (rms). This emittance is smaller than the best quality beam produced by conventional RF accelerator technology such as a photocathode RF-gun[7][8].

These results show that the colliding pulse optical acceleration by two laser pulses has a possibility of small energy spread and low emittance electron injection.

4. Conclusions

We have explored the generation of a high quality electron bunch by using colliding pulse optical acceleration by two counter-propagating laser pulses that are a realistic method for experiments of high quality electron generation. The mechanism is a new one for electron injection and acceleration. We have made a numerical simulation of the optical injection scheme and compared it to the calculation of the optical acceleration. In particular, we have studied the pulse duration of the injected and accelerated electron bunches. The wakefield compressed the electron bunch and the space charge stretched the electron bunch. The colliding pulse acceleration scheme investigated has the ability to produce relativistic electron bunches with low energy spread, low normalized transverse emittance, and short bunch length.

References

1) S. Bulanov, N. Naumova, F. Pegoraro, and J. Sakai, Phys. Rev. E **58**, R5257, 1998
2) D. Umstadter, J. K. Kim, and E. Dodd, Phy. Rev. Lett. **76**, 2073, 1996
3) E. Esarey, R. F. Hubbard, W. P. Leemans, A. Ting, and P. Sprangle, Phy. Rev. Lett. **79**, 2682, 1997
4) C. B. Schroeder, P. B. Lee, J. S. Wurtela, E. Esarey, and W. P. Leemans, Phy. Rev. E **59**, 6037, 1999
5) E. Esarey, C. B. Schroeder, W. P. Leemans, and B. Hafizi, Phys. Plasmas **6**, 2262, 1999
6) S. Masuda, T. Katsouleas, and A. Ogata, Nucl. Inst. and Meth. A **455**, 172, 2000
7) K. Nakajima, Nucl. Instr. and Meth. in Phys. Rès. A **455**, 140, 2000
8) X. J. Wang, M. Babzien, K. Batchelor, I. Ben-Zvi, R. Malone, I. Pogorelsky, X. Qui, J. Sheehan, J. Sharitka, and T. Srinivasan-Rao, Nucl. Instr. and Meth. A **375**, 82, 1996; X. J. Wang, X. Qiu, and I. Ben-Zvi, Phys. Rev. E **54**, 3121, 1999.

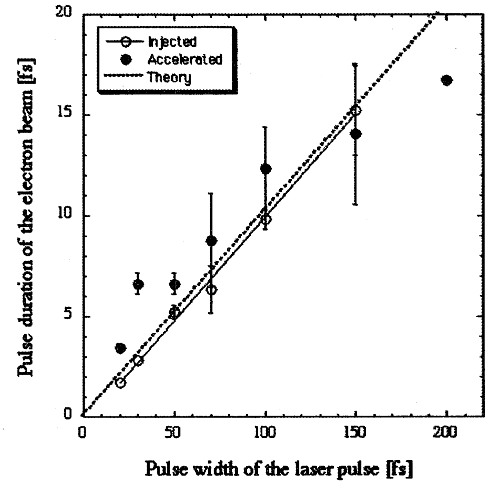

Fig. 1 The pulse duration of the electron beam for a_0=1.0 and a_1=0.4

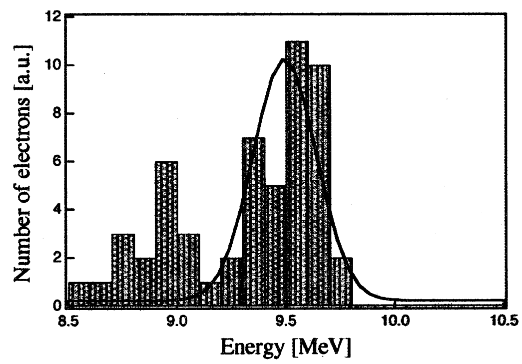

Fig. 2 The energy spectrum of accelerated electrons at n_e=7×10^{17}cm^{-3} for a_0=1 and a_1=0.4

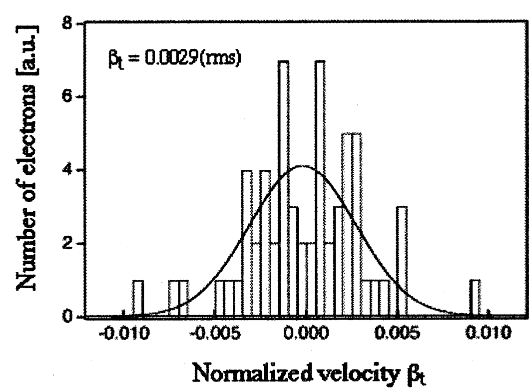

Fig. 3 The distribution of the transverse normalized velocity β_t of the accelerated electrons for a_0=1.0 and a_1=0.4 at n_e=7×10^{17}cm^{-3} and a laser pulse width of 50 fs.