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Simulation study of electron injection into plasma wake fields by colliding laser pulses using OOPIC*

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Abstract An electron injector concept for a laser-plasma accelerator has been developed which relies on the use of counter propagating ultrashort laser pulses. In this paper, we use OOPIC the fully self-consistent, two-dimensional, particle-in-cell code to make a parameter study to determine the bunches that can be obtained through collisions of two collinear laser pulses in uniform plasma. A series of simulations show that one can obtain a short (<10fs) bunch with its charge of about 15pC, and energy spread of about 15%. We also discussed the variation of the transverse spot size of the electron bunch and found the bunch would undergo the betatron oscillations.

Key words LWFA, optical injection, colliding pulse injection, electron acceleration, OOPIC, betatron oscillations

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1 Introduction

Laser-plasma-based accelerators[1, 2] have been conceived to be the next-generation particle accelerators due to the large longitudinal acceleration gradients in excess of 10 GeV/m without the limitations of breakdown in conventional accelerators. In a plasma, the wavelength of the acceleration field is the plasma wavelength, $\lambda_p=2\pi c/\omega_p$, where $\omega_p=(4\pi n_0 e^2/m_e)^{1/2}$ is the plasma frequency and n_0 is the plasma density. If a mono-energetic electron bunch is injected into a wakefield with a density about $n_0 \approx 10^{18}\text{cm}^{-3}$and a plasma wavelength about $\lambda_p \approx 30\mu\text{m}$ and then is accelerated, in order to maintain a small energy spread, the bunch length must be small enough to just cover a small fraction of the wake period, on the order of a few femtoseconds. One femtosecond precise injection is demanded which is beyond the present state-of-the-art performance of photocathode RF electron guns. In order to generate a small energy spread electron bunch, one optical injection scheme using an additional intense ultrashort laser as a kicker has been reported which is called "colliding pulse injection" (CPI)[3, 4]. The precise understanding of CPI concept and the optimization of this process motivate us to simulate the CPI process and the subsequent acceleration by OOPIC code (one two-dimensional Particle-in-Cell code).

The rest of the paper is organized as follows: in Sec.2 we give a brief description of the OOPIC code. In Sec.3 we describe the optical colliding pulse injection scheme. In Sec.4 we present the results of the simulations. The conclusions and discussions are presented in Sec.5.

2 The OOPIC code

The simulation code OOPIC used in our study is an object-oriented two-dimensional relativistic electromagnetic particle-in-cell code written in C++ by J.P.Verboncoeur and collaborators at the University of California at Berkeley[5]. OOPIC can simulate many physical systems including plasmas, beams of charged particles with self consistent and externally generated electric and magnetic fields, low-to-moderate density neutral gases and wide variety of

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boundary conditions. It has electrostatic and electromagnetic field solvers for 2D geometries in both x-y (slab) and r-z (cylindrical) coordinates, and includes Monte Carlo collision and ionization models. The code also can run on parallel machines through Message Passing Interface (MPI).

3 Optical injection schemes in LWFA

In order to produce an electron beam with low energy spread in LWFA, several methods have been proposed[3,4,6—10]. The optical injection schemes[3, 6—8] are especially promising, which use additional ultrashort laser pulses to trigger the electron injection. Umstadter[3] first proposed the "optical injection" concept which uses a second laser propagating perpendicular to the pump laser as a kick to inject the background electron into the accelerating field. Esarey[4] proposed a counter-propagating scheme based on the use of three laser pulses. Fubiani[6] and Kotaki[7] used only two laser pulses to further develope Esarey's idea. For example, in Kotaki's model[7] two counter-propagating ultra-short laser pulses with the same frequence and polarization are used. The 'pump' pulse creates a high amplitude plasma wave with phase velocity near the speed of light and collides with the 'injection' pulse. The laser pulses collide in the plasma and their interference creates a beat wave which is a standing wave with a zero phase velocity and a typical spatial scale $\lambda_0/2$. Due to this small scale length, the axial force of the beatwave is very large: $F_{\rm beat} \approx 2a_0a_1/\lambda_0$. With the zero phase velocity and large axial force, the beat wave can trap and heat some plasma background electrons which then can be injected into the main plasma wave for acceleration to high energies. In this paper, we will use OOPIC to simulate and study Kotaki's model[7].

4 Simulations results

The laser pulses propagating along the x axis in the simulations are modeled as linearly polarized in the z direction with transverse Gaussian profile and have an amplitude variation that at the focus is longitudinally a Gaussian pulse. The length of the simulation box is $L_x = 160$ μm in the X direction and $L_y = 100$ μm in the Y direction. The computational mesh consists of 1600 cells in the X direction and 80 cells in the Y direction with 512,000 computational particles. To avoid edge effects, the pump pulse is launched into a vacuum region of 10 μm following a rise density of 90 μm. The moving window is turned on at $ct = 0.99L_x$ and the pulses collids at $ct = 100$ μm.

In all simulations, the pump ($i = 0$) and injection ($i = 1$) laser pulses both have wavelength, $\lambda_i = 0.8$ μm, and spot size $r_i = 15$ μm. Unless otherwise noted, other parameters are chosen as follows: a_0 from 1.2 to 1.3, a_1 from 0.2 to 0.8, the drive pulse length $c\tau_0 = \lambda_{\rm p}/2$ (standard LWFA), and the injection pulse length $c\tau_1$ from $0.225\lambda_{\rm p}$ to $2\lambda_{\rm p}$. In order to study and optimize the process of CPI, four sets of difference input parameters are simulated: (i) to investigate the plasma density effects on electron beam when we change the density while fix the two laser pulses parameters, (ii) to investigate the effect of

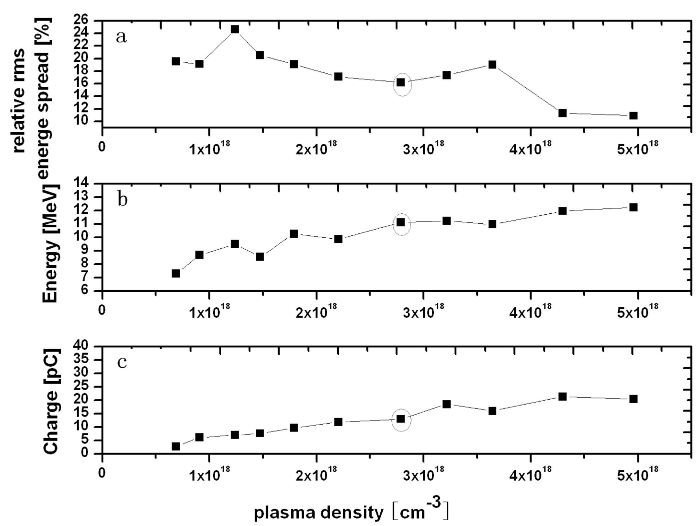

Fig. 1. The relative rms energy spread, electron bunch energy and trapped electron bunch charge versus plasma density for $a_0 = 1.3, a_1 = 0.4$,and $\tau_0 = \tau_1$ =33.3fs. Assume the radius of the electron bunch is $r_i = 15$ μm.

injection pulse duration on electron beam when we change the injection pulse duration while fix the other input parameters, (iii) to study the injection laser intensity effects when we change the injection laser intensity while fix the other parameters, (iv) we also study the transverse spot size of the electron bunch.

Figure 1 displays the relative rms energy spread(a), electron bunch energy(b) and trapped electron bunch charge(c) as a function of plasma density over a range, $6.9\times10^{17}\text{cm}^{-3}$ to $4.96\times10^{18}\text{cm}^{-3}$. Fig. 1(a) shows that the minimum of bunch energy spread occurs near the condition of $\lambda_\text{p}=\pi c\tau_0$[7] ($c\tau_0$ the pump laser pulse duration in the longitudinal direction). In this simulation example, $n_\text{p}=2.789\times10^{18}\text{cm}^{-3}$ is the optimum condition for the trap and acceleration which can obtain an accelerated electron bunch with 15% energy spread, 12 MeV mean energy and 15 pC charge. Fig. 1(b),(c) shows that the mean energy and the bunch charge increase with the plasma density because a higher amplitude wakefield can be obtained in denser plasma.

The relative rms energy spread, electron bunch energy and trapped electron bunch as a function of injection pulse duration varying from 15fs to 133.3fs and the injection pulse intensities varying from a_1=0.3 to a_1=0.8 are separately shown in Fig. 2 and Fig. 3. It can be seen from Fig. 2 that the energy spread, the energy and the charge are not a sensitive function of the injection pulse duration varying from 15fs to 100fs. They also show the electron beam quality is better in high-density $2.789\times10^{18}\text{cm}^{-3}$ than in low-density $1.24\times10^{18}\text{cm}^{-3}$. Fig. 3 indicates that the energy spread is not a sensitive function of the injection pulse intensity over the range, $0.3< a_1 <0.8$.

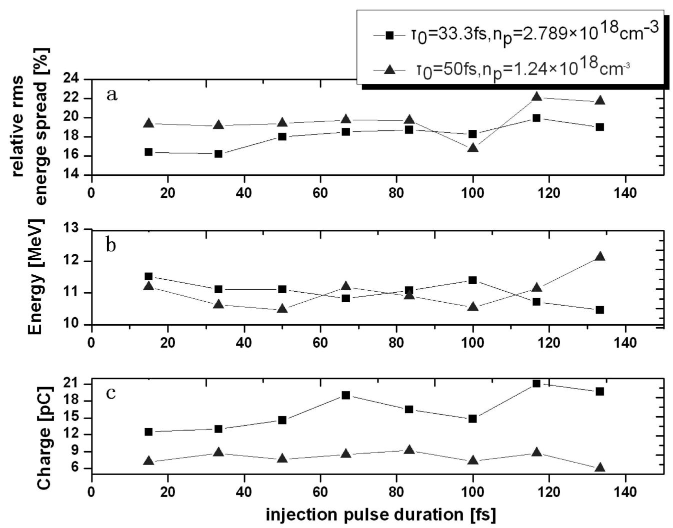

Fig. 2. The relative rms energy spread, electron bunch energy, trapped electron bunch charge versus injection pulse duration for a_0=1.3, a_1=0.4, $c\tau_0=\lambda_\text{p}/2$, n_p=$2.789\times10^{18}\text{cm}^{-3}$and $1.24\times10^{18}\text{cm}^{-3}$.

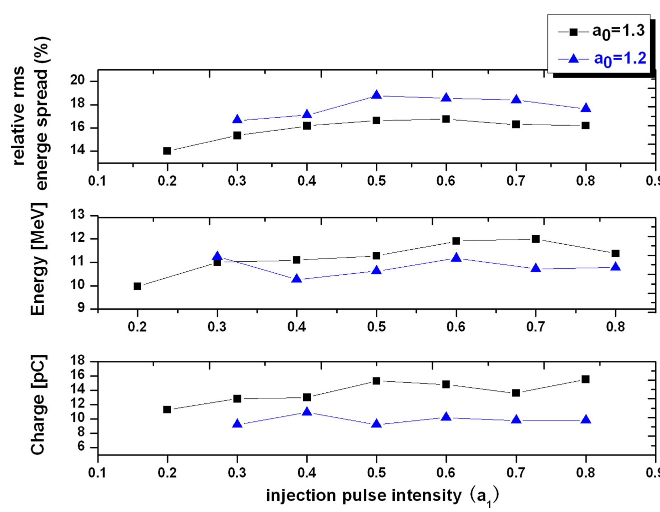

Fig. 3. The relative rms energy spread, electron bunch energy and accelerated electron bunch charge versus injection pulse intensity for a_0=1.3 and1.2, $c\tau_0=c\tau_1=\lambda_\text{p}/2$, n_p= $2.789\times10^{18}\text{cm}^{-3}$.

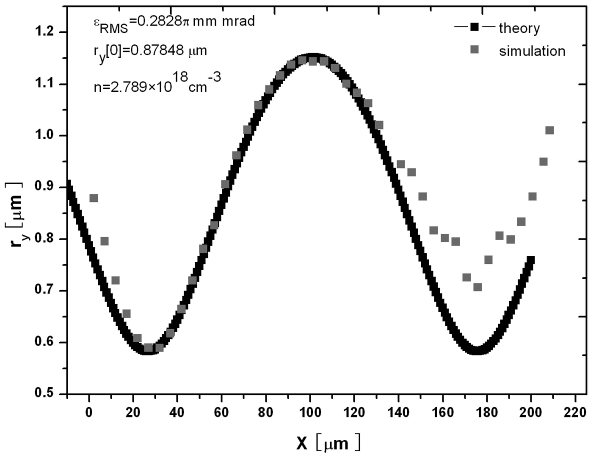

Fig. 4. The transverse spot size r_y varied with the accelerated electron bunch propagating after colliding injection, where $a0$=1.3, $a1$=0.4, $c\tau_0 = c\tau_1 = \lambda_p/2$,$n_p$=2.789×10^{18}cm^{-3}. The red squares are simulation data and the black squares are the prediction of the envelope Eq. (1).

The propagation of accelerated electron bunch through a long, dense column of plasma has time dependent transverse behavior that had been theoretically predicted by Clayton[11] The behavior of the electron bunch with a normalized emittance ε_N is described by the bunch envelop equation.

$$\sigma_r''(z)+[k^2-\frac{\varepsilon_N^2}{\gamma^2\sigma_r^4(z)}]\sigma_r(z)=0\,, \qquad (1)$$

where $k=\omega_p/(2\gamma)^{1/2}c$ is the restoring constant of the plasma, γ is the relativistic Lorentz factor and c is the speed of light. Simulation shows that the electron beam also experiences the transverse betatron oscillation which is consistent with the theoretic equation in Fig.4. In Fig.4 we can see some area which isn't consistent with the theory because the normalized emittance and bunch size of the electron bunch are variational during acceleration, while in the theoretic equation they are constant.

5 Conclusion and discussion

We have shown 2D PIC simulations performed with the code OOPIC of the colliding pulse injection scheme. We have studied the density, the injection pulse duration and intensity effects on electron bunch and obtained a short (<10fs) bunch with about 15 pC charge and about 15% energy spread. In simulations we first observe betatron oscillations of the accelerated electron bunch in CPI and our study shows that the result is consistent with the Clayton's bunch envelope equation.

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