CONTROLLED INJECTION IN THE SHARP PHASE MIXING REGION OF LWFA

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Abstract

To generate the good quality electron bunch, stable fast injection is very important issue in the laser wakefield accelerator (LWFA). One of the self-injection methods is the wave breaking. In this scheme, the density transition scale length is much larger than plasma skin depth. After a new self-injection mechanism using the sharp density transition scheme was proposed, the experiment for the generation of the plasma shock structure, which will be used for the sharp density transition structure, have been conducted. In this scheme, while one can reduce the wave breaking, the electron can be injected effectively using a phase mixing. Thus, the sharp density transition scheme is promising candidate method for the more stable generation of good quality electron bunch. In this scheme, the main issue is that the finding optimum conditions in which the injected electrons only in the first period of laser wake wave are accelerated further. In this paper, optimum conditions of sharp density transition scheme have been studied using Particle-In-Cell simulations. Throughout the extensive simulation work, the optimum conditions for the ongoing experiments at KERI are presented.

INTRODUCTION

A table top size electron accelerator now can be realized due to the development of an ultra high power femtosecond laser. A high power laser can generate a strong longitudinal acceleration field inside plasma, wakefield, which propagates in the plasma with a group velocity of the laser [1]. For the stable operation of the laser wakefield accelerator, the self-injection problem in the early stage is very important issue. Effective early injection can generate short electron bunches and quasi-monoenergetic electron beams stably. After optical injection methods by using two or three high power laser pulses were proposed [2, 3], the controlled injection by colliding laser pulses was demonstrated [4] recently. Although Bulanov's wave breaking scheme [5] for the self-injection is much simpler than optical injection methods but leads to an injected beam pulse with a relatively large phase spread which results in the electron bunch with a large energy spread. And, after a new self-injection scheme using sharp density transition was proposed [6], a plasma shock structure is studied as a feasible condition for the sharp density transition [7, 8, 9]. In this scheme, the scale length, which means the distance between high and low density region, is shorter than the plasma wavelength. This sharp density transition scheme provides very short injection pulse that is phase-locked to the acceleration phase in the laser wake wave and small energy spread. In the sharp density transition scheme, the crucial issue is that the finding optimum density conditions in which the injected electrons in the first period of laser wake wave are accelerated further and the injected electrons in the other periods of laser wake wave gain less energy. The highly reproducible quasi-monoenergetic electron beams can be achieved with this optimum density profile in the sharp density transition scheme. Thus, more detailed investigation of scale length and density transition ratio effects on the electron injection and acceleration are needed. In this paper, we report simulation results over the scale length and density transition ratio effects on the generation of good quality electron bunch in the first period of laser wake wave. For this purpose, a two-dimensional (2D) PIC simulations were performed by using the fully relativistic and electromagnetic XOOPIC code [10].

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SIMULATION RESULTS

When the laser pulse propagates through a plasma, a laser wakefield is generated behind the laser pulse and its strength depends on the pulse duration for a given plasma density. In our ongoing experiments, laser FWHM (full width half maximum) pulse duration is fixed to $35fs$, thus the field strength depends only on the plasma density. After propagation in a high density region, the laser beam is sent to the sharp density transition region with a finite scale length. In this work, to find an optimum conditions for the generation of good quality electron bunch in the first period of laser wake wave, the simulation work has been performed for the various parameter space of the scale length and the density transition ratio.

In the simulations, the moving window, which moves at the speed of light, has a size of $80\mu m \times 80\mu m$, and it has 1600×400 grids and 2.5×10^6 particles. The laser beam has a wavelength (λ) of $1\mu m$, a FWHM pulse duration (τ_L) of $35fs$ and intensity (I) of $5.5 \times 10^{18} W/cm^2$, which means normalized vector potential $a = 2$ (for $\lambda = 1\mu m$, the normalized vector potential can be expressed as $a = 0.85\times10^{-9}\sqrt{I}$). The laser beam is focused to a focal spot size of $10\mu m$, which is located at the density transition starting point. The laser pulse is initially launched in vacuum, then, it moves into a uniform plasma density (n_H, high density region). After propagation in a high density uniform plasma, the laser is sent to the sharp density transition region with a finite scale length defined as the distance of decreasing density region between high and low plasma density region as shown in Fig. 1. In this work, the scale length (L_s) ranges from 1 to $30\mu m$. The electron trapping occurs in the density transition region and then

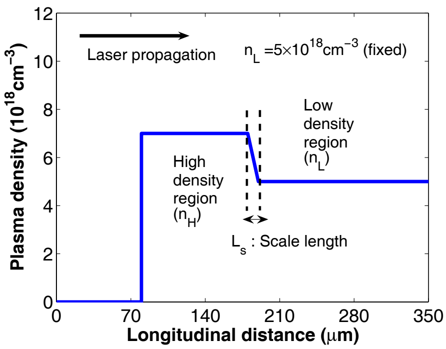

Figure 1: Longitudinal density pro£le.

trapped electrons are accelerated further in the low density region. Therefore, the density of low density region(n_L) is £xed on $5 \times 10^{18} cm^{-3}$, which is an optimum plasma density for ef£cient generation of laser wake£eld for a $35 fs$-laser pulse duration in this simulation. The plasma density of high density region ranges from $5.5 \times 10^{18} cm^{-3}$ ($n_L/n_H = 0.7$) to $1 \times 10^{19} cm^{-3}$ ($n_L/n_H = 0.5$).

Figure 2 shows the simulation results for the case of $1\mu m$ scale length with 70% (n_L/n_H=0.7) density transition ratio at t=0.8 ps. Figure 2(a) indicates that a signi£cant number of background plasma electrons are self-injected into the acceleration phase in the £rst period of laser wake wave after the laser beam passes the density transition region. The longitudinal energy phase plot of the plasma electrons over the 1 MeV energy is shown in the Fig. 2(b). The injected particles in the £rst period of the laser wake wave are shown inside the dashed ellipse. This electron bunch is not generated without density transition. This is the evidence of the self-injection phenomenon by the sharp density transition scheme. Figure 2(b) also shows that there are some other injected electrons in the second period. Compared with the injected electrons in the £rst period of laser wake wave, the electrons of the second period gain less energy because these electrons are accelerated in different phase in which the wake£eld strength is weaker than the £rst period. As the injected particles are accelerated by the laser wake wave, their energies increase.

In order to £nd an optimum parameter condition for the scale length and the transition ratio, we carried out simulation work for various parameter ranges. Figure 3(a) shows the number of accelerated electrons (NAE) of the bunch in the £rst period with the scale length for two different density transition ratios at saturation point. The NAE decreases linearly with an increasing scale length. In addition, the NAE increases with the increasing plasma density in the high density region. In the laser driven trapping, because the only electrons in the high density region are injected [11], more electrons are injected as the density of the high density region increases. Although the NAE decrease with the increasing scale length, the bunch size is independent of the scale length as shown in Fig. 3(b). It depends on the transition ratio. In the saturation point, the energy of the

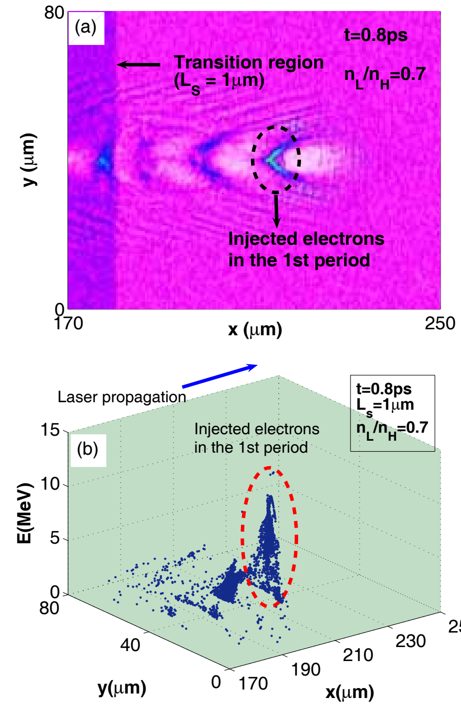

Figure 2: The simulation results for the $1\mu m$ scale length with 70% density transition case at $t = 0.8ps$. (a) Position plot (x, y), (b) Longitudinal energy phase plot of plasma electrons.

accelerated electrons is relativistic high energy. Thus it is expected that the transverse bunch size is not affected by space charge effect. This is evident if the $1\mu m$ scale length with 70% transition ratio and $30\mu m$ scale length with 50% transition ratio cases are compared. In these two cases, NAE is almost similar but the transverse bunch size is very different. This indicates that the transverse bunch size is not affected by space charge effect. The bunch size can also depend on the acceleration length of £rst period in the low density region, but in this scheme, after laser passes the transition region, the density of low density region is £xed. Therefore, the bunch size depends only on the transition ratio in our simulations. We checked the longitudinal energy spread ($\Delta E_{FWHM}/E_{peak}$) of the injected electrons in the only £rst period with the scale length for the two density ratio cases at the saturation point as shown in Fig. 3(c). In the 70% transition ratio (solid line), the energy spread is increasing, as the scale length increases. In the 50% transition ratio (dashed line), although the energy spread is small in all scale length range, however the transverse bunch size is larger. To clarify the optimum density transition ratio, we checked the detailed transition ratio effect on NAE. Figure 3(d) shows the NAE in the bunch with various transition ratios for the $1\mu m$ scale length case. There is rapid decreasing of NAE over transition ratio of 0.7. In the phase mixing mechanism, the length of mixing region depends on the transition ratio for the £xed scale length. This indicates that the electron injection into the acceleration phase

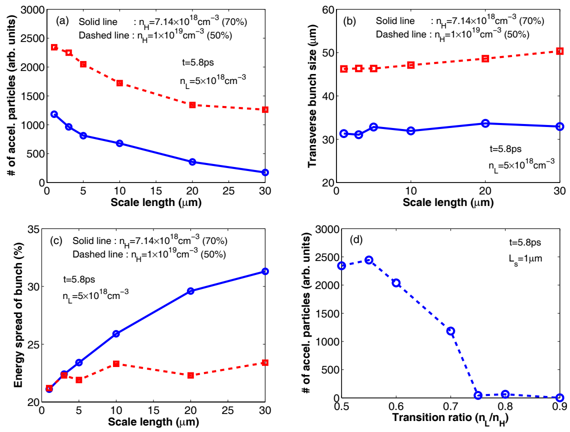

Figure 3: Number, transverse size and energy spread of the accelerated electrons in the £rst period of laser wake wave at the saturation point for various parameter regimes of the scale length and the density transition ratio. (a) Number of the accelerated electrons (solid line : 70% transition ratio, dashed line : 50% transition ratio), (b) Transverse bunch size of the accelerated electrons (solid line : 70% transition ratio, dashed line : 50% transition ratio), (c) Energy spread of the accelerated electrons (solid line : 70% transition ratio, dashed line : 50% transition ratio) and (d) Number of accelerated electrons in the £rst period of laser wake wave at the saturation point with various density transition ratios.

is affected by the length of the mixing region.

In this simulation work, we can conclude that there exists an optimum parameter condition for obtaining the good quality electron bunch (in this work, $1\mu m$ scale length and 70% density transition ratio) for the our ongoing experiment.

CONCLUSION

In this study, the scale length and the density transition ratio effects on the generation of good quality electron bunch by a sharp density transition in laser-driven LWFA is investigated using 2D-PIC simulations. The number of accelerated electrons of the electron bunch in the £rst period of laser wake wave is strongly related to the plasma density in the higher density region. The bunch length depends only on the density transition ratio at the saturation point and shorter bunch length is generated in the higher density transition ratio case. In this case, the energies of injected electrons are much higher than lower density transition ratio case. The smaller energy spread of the electron bunch in the £rst period is generated in the shorter scale length case. Throughout this work, we can conclude that the charge of electron bunch is proportional to the plasma density in the high density region and the density transition ratio is very important parameter for the generation of good quality electron bunch. Optimum parameter condition for the generation of quasi-monoenergetic, smaller energy spread and electron bunch size could be found through the parametric simulation work.

REFERENCES

[1] T. Tajima and J. M. Dawson, Phys. Rev. Lett. 43 (1979) 267.

[2] D. Umstadter, J. K. Kim, and E. Dodd, Phys. Rev. Lett. 76 (1996) 2073.

[3] E. Esarey, R. F. Hurbbard. W. P. Leemans, A. Ting, and P. Sprangle, Phys. Rev. Lett. 79 (1997) 2682.

[4] J. Faure, C. Rechatin, A. Norlin, A. Lifschitz, Y. Glinec, and V. Malka, Nature 444 (2006) 737.

[5] S. Bulanov, N. Naumova, F. Pegoraro, and J. Sakai, Phys. Rev. E 58 (1998) R5257.

[6] H. Suk, N. Barov, J. B. Rosenzweig, and E. Esarey, Phys. Rev. Lett. 86 (2001) 1011.

[7] J. U. Kim, N. Hafz, and H. Suk, Phys. Rev. E 69 (2004) 026409.

[8] H. Jang, J. Kim. S. Yoo, M. Hur, H. Suk, M. Cho, and W. Namkung, J. Korean Phys. Soc. 50 (2007) 1466.

[9] J. Kim, H. Jang, S. Yoo, M. Hur, I. Hwnag, J. Lim, V. Kulagin, H. Suk, I. Choi, N. Hafz, H. Kim, K. Hong, T. Yu, J. Sung, T. Jeong, Y. Noh, D. Ko, and J. Lee, J. Korean phys. Sco. 51 (2007) 397.

[10] J. P. Verboncoeur, A. B. Langdon, and N. T. Gladd, Comput. Phys. Commun. 87 (1995) 199.

[11] H. Suk, H. Lee, and I. Ko, J. Opt. Soc. Am. B 21 (2004) 1391.