NUMERICAL STUDY OF INJECTION MECHANISMS FOR GENERATION OF MONO-ENERGETIC FEMTOSECOND ELECTRON BUNCH FROM THE PLASMA CATHODE

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Abstract

Acceleration gradients of up to the order of 100GV/m and mono-energetic electron bunch up to 200MeV have recently been observed in several plasma cathode experiments. However, mechanisms of self-injection in plasma are not sufficiently clarified, presently. In this study, we carried out 2D PIC simulation to reveal the mechanisms of Laser Wake Field Acceleration (LWFA). Electron density gradient at vacuum-plasma interface is important condition for electron's self-injection owing to plasma wave breaking. Steep electron density gradient (~ plasma wave length) causes rapid injection and produces an electron bunch with rather high charge and less than 100fs duration. By this calculation, we obtained the electron bunch width of about 40fs and the maximum energy achieved more than 20MeV. The charge amount of >3MeV electrons in one bunch was estimated as 50pC with the steep density gradient, while it was 10pC with the gentle one.

INTRODUCTION

The acceleration of electrons by laser-driven plasma wake fields has been an extremely active area of the laserplasma study [1]. Acceleration gradients of up to the order of 100GV/m and mono-energetic electron bunch up to 200MeV have recently been observed in several experiments [2-11]. It suggests that Laser Wake Field Acceleration (LWFA) can realize compact, tabletop electron accelerators. In addition, accompanying recent remarkable progresses in high intensity ultrashort pulse lasers, pulse X-ray sources have been under development for time-resolved measurements. There are several sources of picosecond pulse X-rays and now we are aiming to generate femtosecond X-rays. The relativistic Thomson scattering of femtosecond laser light by femtosecond electron bunch can produce femtosecond Xrays.

The wake field is generated after a high intense laser pulse propagating through plasma with the following mechanism [1]. The ponderomotive force proportional to the laser intensity gradient moves electrons along the laser propagation. After the laser has passed, remaining ions pull the electrons back and then the plasma oscillation begins, which generates the wake field propagating in the same direction of the laser, at the phase velocity of nearly the speed of light. By injecting electrons to be trapped by the wake field, the electrons can be continuously accelerated up to extremely high energy. Furthermore, the duration of the injected electron bunch becomes several tens of femtoseconds because the typical wave length of the wake field is around 10um.

There are several ways to inject electrons into the wake field. A conventional RF accelerator can supply high quality electron beam [2-3], however it is difficult to synchronize the electron bunch with the wake field. In the first place, use of a conventional accelerator is not in accordance with the object for compact and tabletop accelerators. In other ways, two or several laser pulses are utilized for injection and acceleration of electrons [4-6], but that has difficulties in synchronization between the wake field and the injection and also requires complex setup.

The wave-break injection is a rather simple way in which we use a single laser pulse to generate energetic electrons and wake fields [7-8]. However, this injection requires as short electron density gradient at the vacuumplasma interface as the wave length of the plasma wave. In the region of the laser intensity I of 1×10^{19} W/cm², the wave breaking appears when the amplitude of the plasma wave exceeds the threshold $E_{th} \sim [2(\omega/\omega_{pe}-1)]^{1/2} (mc\omega_{pe}/e)$, where ω and ω_{pe} are the laser and the plasma frequency, m the electron mass, e the electron charge, c the speed of light in vacuum. This excess occurs in plasma with a rather steep gradient of the electron density as $N/(dN/dx) \sim \lambda_{pe}$, where N is the electron density, λ_{pe} the wave length of the plasma wave $\lambda_{pe}=2\pi c/\omega_{pe}$. However, mechanisms of the self-injection are not sufficiently clarified, presently.

Since a typical gas jet forms much longer density gradient (~350um) in actual experiments [8], a prepulse of the laser is used to generate a shockwave in plasma and the shockwave makes rather steep density gradient [8]. Generation of femtosecond X-rays requires enough number and high energy of electrons and femtosecond bunch duration.

In the present work, we carried out 2D Particle-In-Cell (PIC) simulations of the wave-break injections and femtosecond electron bunch generations to reveal their mechanisms. We show the differences between the case of 5um and 150um of the electron density gradient.

SIMULATION

We performed fully relativistic 2D PIC simulations to study effects of electron density gradient on wave breaking injections in plasma for the LWFA. The code employs the "moving window" technique [12].



Figure 1: Initial electron density distribution, *l* set to 5um and 150um for steep and gentle gradient cases, respectively.



Figure 2: Electron energy distribution at the plasma density of 3×10^{19} cm⁻³ with steep:5um (solid line) and gentle:150um (dotted line) density gradient.

An initial electron density distribution is shown in Fig.1, where *l* is the electron density gradient at vacuum-plasma interface, set to 5um and 150um for steep and gentle gradient cases, respectively. An s-polarized laser pulse with 50fs duration (Full Width at Half Maximum) is focused on the interface with the spot size of 7um diameter and the laser intensity of 1×10^{19} W/cm². The top value of electron density is set to 3×10^{19} cm⁻³ for the laser intensity to exceed the critical power for self-focusing $P_{cr}=17(\omega/\omega_{pe})^2$ GW. The size of the window moving at the speed of light in vacuum is 164um×120um (2800×2048 cells) and we used 16 particles per cell. No plasma ionization is included. The results of electron energy distributions generated from the plasma are shown in Fig. 2. The solid line is for steep gradient case and the dotted



Figure 3: The spatial distribution of electron longitudinal momentum P_x at the laser intensity of 1×10^{19} W/cm² and the plasma density of 3×10^{19} cm⁻³ with (a) steep:5um and (b) gentle:150um density gradient.

line is for gentle. The charge amount of >3MeV electrons in one bunch was estimated as 50pC with the steep density gradient, while it was 10pC with the gentle one. Figure 3 shows the spatial distribution of electron longitudinal momentum P_x at the laser intensity of 1×10^{19} W/cm² and the plasma density of 3×10^{19} cm⁻³ with (a) steep:5um and (b) gentle:150um density gradient. The electron bunch width of about 40fs and the maximum energy achieved more than 20MeV have been obtained.

CONCLUSION

We carried out fully relativistic 2D PIC simulations of the wave-break injections and femtosecond electron bunch generations to reveal their mechanisms. Rather steep gradient which is comparable to the plasma wave length, leads efficient wave-break injections of electrons into the plasma wake field. The electron bunch width became about 40fs and the maximum energy achieved more than 20MeV. The charge amount of >3MeV electrons in one bunch was estimated as 50pC with the steep density gradient, while it was 10pC with the gentle one. In a experiment, using a pre-pulse of a high intense laser pulse, we can make shockwave at the vacuumplasma interface to form steep density gradient and obtain electron bunches with rather high charge.

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