Stochastic heating and acceleration of electrons by high intensity lasers in inhomogeneous plasmas

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Abstract. Electron acceleration by sub-picosecond relativistic intense laser pulse propagating in inhomogeneous plasmas has been studied by one-dimensional (1D) particle-in-cell (PIC) simulations. It is found that the effective temperature of electrons scales as \(T_e \sim I_0 \tau_L^{1/2}\), where \(I_0\) is the laser intensity and \(\tau_L\) is the laser pulse duration. The high temperature electrons produced in the earlier stage are mainly due to the stochastic acceleration in the colliding laser fields, where the backward propagating fields are produced in part by the Raman backscattering in the underdense plasma region as well as by reflection from the overdense plasma region. The induced electrostatic fields in inhomogeneous plasma can accelerate electrons randomly, which contribute to the increase of the electron temperature at later stage.

1. Introduction

With the development of tabletop ultraintense lasers, ways of producing energetic electron beams by ultra-short high intensity lasers have received renewed interest due to their potential applications [1-10], such as the fast ignition of ICF targets by high current multi-MeV electron beams, compact x-ray and \(\gamma\)-ray sources for laser-driven radiograph, generation of collimated energetic ion beams etc. Depending on the plasma parameters, fast electrons can be produced by plasma-wave acceleration, laser acceleration with assistance of additional fields or by the laser ponderomotive force, mixed acceleration from both the transverse and longitudinal fields etc. Two particular mechanisms, including the betatron resonance acceleration [7] and the stochastic heating and acceleration [8] were proposed lately. Both of them enable electrons to be accelerated much beyond the usual ponderomotive potential level. In fast ignition schemes, the involved laser pulse duration is typically at the picosecond level and the inhomogeneous plasma density scale-length may be a few tens of the laser wavelength, which can be formed by free expansion of the solid surface when a prepulse arrived at hundreds of picoseconds ahead of the main pulse [11,12]. In this case, Raman
backscattering fields or reflected fields from the critical surface is inevitable. Together with the incident laser field, they may trigger stochastic heating and acceleration. Since previously studies of stochastic acceleration are only in homogeneous tenuous plasma, in this work, we report numerical investigation of electron heating and acceleration in inhomogeneous plasma by means of a 1D PIC code [13]. The scaling of the hot electron temperature with the laser and plasma parameters has been found and the role of stochastic acceleration has been clarified since other accelerating mechanisms associated with the multi-dimensional effects, such as the betatron acceleration, have be excluded.

2. Electron temperature scaling and acceleration mechanisms

In our simulations, p-polarized laser pulses with a sine-square profile \( a = a_0 \sin^2 (\pi t / \tau_L) \) is incident normally from left and the plasma has an exponential density profile \( n(x) = n_0 \exp(-x/L) \). Here \( a \) is the vector potential normalized by \( mc^2/e \) and its peak is \( a_0 \), which relates to the laser intensity with \( I_L = a_0^2 \times 1.37 \times 10^{18} W/cm^2 \mu m^2 \). \( \tau_L \) is the laser pulse duration normalized by the laser cycle \( \tau_0 = 2\pi/\omega_0 \), and \( L \) is the plasma density scale-length. The maximum plasma density is higher than the critical one corresponding to the incident laser and the ions are assumed to be immobile since their mobility has negligible effect on electron acceleration under our simulations conditions, as confirmed by our additional simulations.

![Figure 1](image)

Taking \( L = 30 \lambda_0 \), \( \tau_L = 150 \tau_0 \), \( a_0 = 3 \), figure 1(a) shows typical snapshots of electron energy distributions at different times, \( t = 30 \lambda_0 \), \( \tau_L = 150 \tau_0 \). (b) Final electron energy distributions for different laser intensities, \( L = 30 \lambda_0 \), \( \tau_L = 150 \tau_0 \). (c) Dependence of final electron temperature on laser intensities for different plasma scale-length and different laser pulse duration, respectively, for (c) \( \tau_L = 150 \tau_0 \), (d) \( L = 30 \lambda_0 \).

At about \( t = 280 \tau_0 \), the electrons get the highest effective temperature. At about \( t = 320 \tau_0 \), all the laser fields, including the incident laser field and the contour-propagating fields, propagate out of the plasma.
plasma and we get the final electron effective temperature $T_{\text{eff}}$. Figure 1(b) shows electron energy distributions for different laser intensities and figure 1(c) illustrates the dependence of the electron effective temperature on laser intensities, which suggests:

$$T_{\text{eff}} \approx \kappa I_0 \propto I^{1/2}.$$  \hfill (1)

The scaling of the temperature with laser intensities like $\sim I^{1/2}$ coincides with the results of other theories and simulations under different circumstances [6, 7]. This temperature scaling is valid for different plasma scale-lengths. But the longer the plasma scale-length, the larger the factor $\kappa$ in Eq. (1) is, because there is a larger underdense plasma region in the longer scale-length plasma, where the laser acceleration can occur in a longer distance. Figure 1(d) shows the electron temperature increases with the pulse duration like $\sim t_{\text{L}}^{1/2}$, in agreement with the scaling of electron temperature on laser absorption rate in Ref. [13]. This is different from ponderomotive force acceleration, where the electron temperature mainly depends on the laser intensity and is independent of the pulse duration.

**Figure 2.** (a) The backward-propagating fields; (b) Fourier spectrum of (b); (c) Electron energy get from longitudinal fields versus those from transverse fields at $t=70\tau_0$. (d) Electron momentum distributions at $t=70\tau_0$, $a_0=3$, $\tau_1=150\tau_0$, $L = 30\lambda_0$.

Figures 2(a) and 2(b) show the backward-propagating fields and its spectrum, respectively. When a relativistic-intensity laser pulse propagates in inhomogeneous plasma, the Raman scattering is not restricted to occur only under quarter of the critical density. It will develop in all density regions the laser pulse can propagate [14-16]. The Raman backscattering, forward scattering and modulation instability merge together in the $(k, \omega)$ space and the Raman backscattering can reach saturation very quickly. So before the laser field reflected from the critical surface (around $x=100\lambda_0$), the Raman backscattering wave can be seen in figure 2(a). Their spectrum shows a supercontinuum structure, which is typical for high intensity laser propagation in underdense plasma [14]. All the backward-propagating laser fields can play as the second counter-propagating field to trigger stochastic heating and acceleration of electrons in the plasma.
To examine where the electrons gain energy, one can make use of the relation $\gamma = 1 + \Gamma_\parallel + \Gamma_\perp$ following the equation of motion for electrons [7, 8]. Here $\Gamma_\parallel = -\int_0^t \text{d}t' E_x v_x$ is the energy gain from the longitudinal electric field and $\Gamma_\perp = -\int_0^t \text{d}t' E_\perp v_\perp$ represents the direct laser acceleration by the transverse field. $E_x$ and $E_\perp$ are normalized longitudinal and transverse electric fields, respectively. From figure 2(c) it can be seen that most of the electron energy comes from the transverse fields or the laser fields at the early stage. That is stochastic heating and acceleration dominate in this period. The corresponding momentum distributions [shown in figure 2(d)] illustrate similar features. Although electrons are accelerated by the laser fields, they move mainly along the laser axis due to the Lorentz force. Later, some energetic electrons lose energy and some low energy electrons gain energy under the action of the gradually excited electrostatic fields. Finally the electron energy gain from the longitudinal fields is comparable to that from the transverse fields.

3. Conclusion
Electron acceleration by interaction of sub-picosecond intense laser pulses with inhomogeneous plasma is studied through 1D PIC simulations. It is found that the produced hot electrons have a quasi-thermal energy spectrum and the effective temperature scales with the laser intensity and pulse duration as $(I \cdot \tau_L)^{1/2}$. Either with longer plasma density scale-lengths or with longer laser pulse durations, one can get larger electron temperatures. At the beginning, electrons in the underdense plasma are mainly accelerated by stochastic heating and acceleration and the resulting electron temperatures are much higher than the laser pondermotive potential energy. At the later stage, the electrostatic fields induced by the laser pulse through Raman scattering and ponderomotive force effect tend to heat electrons randomly to even higher temperatures.

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