The effect of increasing the laser pulse intensity on the energy spectrum of electrons in the interaction of a long rise-time laser pulse with Hydrogen atoms

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Abstract

In this paper, the effect of laser pulse intensity on the energy spectrum of electrons in the interaction of a laser with Hydrogen atoms is investigated using PIC simulations. The simulation results are used to compare electron energy distribution functions in the field-ionized plasma (plasma made due to field ionization) and in the pre-plasma. For long rise-time pulse (here 60 fs), although the maximum energy of the electrons is the same in both cases, the energy bandwidth (average electron temperature) of the electron distribution function in the field-ionized plasma is larger than the pre-plasma case. In addition to the increase in laser pulse intensity, the maximum energy of the electrons also increases in two states. This may be due to the delay in meeting Mendonca's condition for the chaos to occur.

Keywords: Laser pulse intensity, PIC simulation, Energy spectrum

Introduction

The ability of generating highly energetic electrons in interaction of intense laser pulse with plasma is one of the most interesting features in laser-plasma physics that has great potentials for many applications including ion acceleration, X-ray generation, and medical applications including proton therapy [1-3]. In this regard, the energy spectrum of electrons can provide useful information about plasma heating and various mechanisms of acceleration and energy gain. Different acceleration mechanisms such as the wake-field acceleration, the direct laser acceleration, and stochastic acceleration [4] have been proposed. The last mechanism is related to the stochastic acceleration of electrons in the presence of two counter-propagating laser fields. It was found earlier from particle-in-cell (PIC) simulations that through this scheme, energetic electrons can be generated higher than the ponderomotive potential of the first laser pulse [5]. In another work, it was shown that in sufficiently long laser pulses, the backward Raman scattered radiation can act as second electromagnetic radiation. Therefore, energetic electrons are produced through the stochastic mechanism [6] in the interaction of the intense laser pulse with under-dense plasma. In fact, the Mendonca criteria $a_1 a_2 = 1/16$ between the normalized vector potentials of the incident radiation a_1 and Raman backscattered radiation a_2 is satisfied [4], and chaos happens.

In this paper, the effect of increasing the laser pulse intensity on the energy spectrum of electrons in the interaction of an intense laser pulse with Hydrogen atoms is investigated using the PIC simulation code which includes the field ionization. To achieve this goal, three simulations are performed for three laser pulses with constant lengths of 300 and different normalized intensity $a_0 = 1$, $a_0 = 2$, and $a_0 = 3$ ($a_0^2 \square I\lambda_\mu^2 / 1.37\times10^{18}$). The Hydrogen neutral atoms density is $n_0 = 0.01\ n_{cr}$ (n_{cr} is the critical density). The results show that, as the laser intensity increases, the electrons reach higher energies. It is clear that there is no difference between the maximum energy of the electrons in the field-ionized plasma and the pre-plasma.

Simulation parameters

Here, the simulation results have been done by using Smilei code [7]. Smilei is a fully relativistic and parallel PIC code that uses ADK-theory[8], the field ionization has also included. In our specific case, several simulations have been run using a one-dimensional version of the code, taking into account the following initial parameters: The Hydrogen neutral atoms density and plasma electrons density in the pre-plasma case have a step like profile in the range of $x = [85 - 220]\mu m$. The length of the simulation box is investigated to be $[0 - 270]\mu m$ with 48 particles per cell and spatial resolution $dx \approx 0.01\times 2\pi\ \mu m$ per wavelength. The conditions of open boundary and reflecting are respectively utilized for the fields and the particles. For a trapezoidal profile in space and time at wavelength $1\,\mu m$, the p-polarized laser pulse is emitted along the x-direction. The pulse envelope is comprised of three different time durations [PL_1, PL_2, PL_3]. PL_1 duration time: the pulse envelop rises, PL_2 duration time: the envelop of the pulse is constant, and PL_3 duration time: the pulse envelop fall as symmetrical.

Simulation results and discussion

To investigate the effect of increasing laser pulse intensity on the energy spectrum of electrons in the interaction of laser pulses with Hydrogen atoms, we have performed simulations with different laser pulses. In the following, 3 pulses are selected as a sample. In Fig. 1, the electron energy spectrums for three pulses with length [60, 180, 60]fs and intensity (a) $a_0=1$, (b) $a_0=2$, and (c) $a_0=3$ are respectively presented at t=650 fs for Hydrogen atoms density $n_0=0.01\ n_{cr}$. In each of these figures, the energy spectra of the electrons in the two states of field-ionized plasma and pre-plasma are compared. According to Fig.1, the electron distribution function of field-ionized plasma is wider and decreases with a soft slope, whereas in the pre-plasma case it falls sharply. It means that the average electron temperature is higher for the field-ionized plasma than in the pre-plasma case. Also, it is clear that with increasing the pulse intensity, the energy of the electrons increases, and at an intensity of $a_0=3$ it reaches maximum energy of 11MeV.

The results of the previous researches [9, 10] show that for the pulses with smooth rise-time (such as 60 fs), the backscattered Raman radiations are generated in the early times of interaction. In this case, if the amplitude of these Raman backscattering radiations meets the Mendonca threshold limit $a_1a_2=1/16$, the chaos occurs. According to the results obtained from the energy spectrum of electrons, it seems that, when the intensity of the laser pulse increases, the occurrence of chaos, in other words, the fulfillment of Mendonca's condition, is delayed. Thus, the electric wake-field behind the laser pulse has opportunity to increase the its amplitude, and as the chaos occurs, the electrons reach higher energies

Conclusions

In this work, the effect of the laser pulse intensity variation on the electron energy distribution in the interaction of strong laser pulse with Hydrogen atoms is studied. For this purpose, one-dimensional PIC simulation code (Smilei code [7]) has been used. Comparison of the results obtained in laser pulse propagation in the field-ionized plasma with the pre-plasma shows that the ionization can affect the energy bandwidth of the electron distribution function.

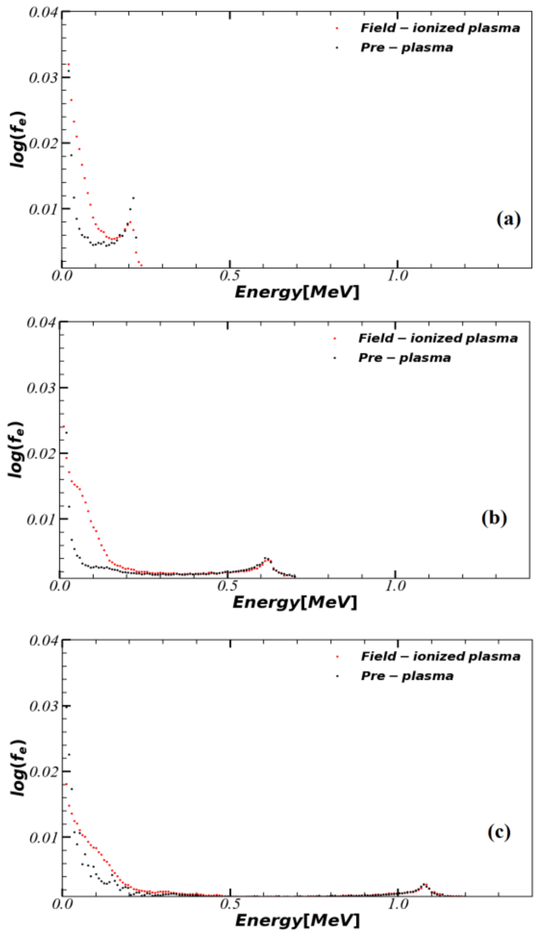

Fig. 1: the electron energy spectrums for three pulses with length [60, 180, 60]fs and intensity (a) $a_0=1$, (b) $a_0=2$, and (c) $a_0=3$ at t=650 fs for Hydrogen atoms density $n_0=0.01\ n_{cr}$.

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