Impact of Ionization on Fast Electron Emission Directions

in High-Intensity Short-Pulse Laser-Target Interactions

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1. INTRODUCTION

A significant part of the laser energy is transformed into the kinetic energy of fast electrons in short pulse high intensity laser solid target interactions. Fast electron generation has been vigorously studied in connection with Fast Ignition of Inertial Confinement Fusion, acceleration of protons and ions and generation of ultrashort hard X-ray pulses. Many theoretical and experimental papers on the energetic spectrum of accelerated electrons were published. As angular spectrum of fast electrons has a profound effect on fast ion acceleration, and on the size of X-ray emission spot, well collimated fast electron beam is advantageous.

In this paper, we study acceleration of fast electrons in ultrashort pulse high intensity laser solid target interactions using PIC code with variable ionization. In most of the previous PIC simulations, constant ion charge was assumed and the ionization processes was neglected. Some simulations included ionization processes via variable charge and mass of existing macroparticles, and thus electrons released during laser plasma interaction cannot be distinguished. In our code, we have included optical field ionization and the new free electrons released from ions are injected into the simulation box with zero kinetic energy. Due to nonlinear effects in laser interactions with dense plasmas, the electrons released from inner shells near the laser pulse maximum are often displaced from other electrons in the velocity space. For linear polarization, these electrons acquire high velocity in the direction of laser electric field. In the case of normal laser incidence, symmetrical pattern of high energy electrons with large angles to the target normal is observed. This effect strongly depends on the target material and the laser parameters.

2. SIMULATION MODEL

To study acceleration of fast electrons during laser target interaction, we use a 1D3V relativistic electromagnetic code, which evolved from the code LPIC++ [1]. Into this code, we have implemented electric field ionization using a Monte Carlo approach, similarly like in [2]. To calculate the ionization rate, we use the ADK formula [3], which depends on the instant local electric field amplitude. The energy spent in ionization is subtracted from the field by introducing an

artificial ionization current. Electrons released during ionization are injected into the simulation box with zero initial velocity with respect to the ions, from which they are released.

3. RESULTS AND DISCUSSIONS

Interaction of the normally incident, p-polarized, 45 fs long, laser wave with the wavelength 800 nm and the maximum intensity 10^{19} W/cm^2 with an aluminum plasma is studied in this paper. The aluminum target has initial ion charge 3 and the density profile on its surface is exponential with a slightly overestimated characteristic length of 4λ. As the optical field ionization takes place mainly in the undercritical plasma in front of the laser reflection point, we use this scalelength to enable the ionization effects to show up significantly. The simulations are calculated either with or without variable plasma ionization. For comparison, in some simulations, the laser wave polarization is switched to circular, or the aluminum target is replaced by titanium and the pulse length is extended to 65 fs keeping the same laser energy (7×10^{18} W/cm^2).

As the initial ion charge, is relatively low and the electric field of the laser wave is strong, the number of free electrons in the undercritical plasma increases due to tunneling ionization several times during the interaction. The electrons from the outer shells are released during the first cycles of the laser wave. They are set free in the electric field maxima of the laser wave cycles, where the other, already free electrons have nearly zero velocity. The newly released electrons therefore behave like, if they were free already initially.

Figure 1: The velocity phase space in one simulation cell, when a new electron (red) from an inner shell is released. The other free electrons are black. Velocity is in the units of the speed of light.

The same situation does not apply to electrons released mostly from the inner shells later during the interaction, near the laser pulse maximum. These electrons were studied recently in the context of laser based accelerators [4], as they are injected into the laser wave near the optimum time for subsequent laser acceleration. The situation studied here, is however different. Due to nonlinear effects in laser interaction with the dense plasma close to the target surface (e.g. harmonic generation, etc.) the forward propagating and the reflected laser wave build up an inharmonic field in front of the target. In such field, free electrons do only rarely have zero transversal velocity in the maxima of the electric field in each laser cycle and then, the newly
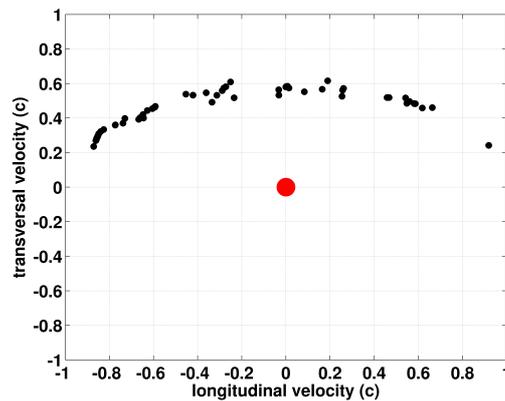
released electrons find themselves on a different place in the velocity phase space. The situation is demonstrated in the velocity phase space snapshot of one simulation cell in Fig. 1. The initially free electrons are dyed black, the electron newly released from 2s shell of Al ion is dyed red.
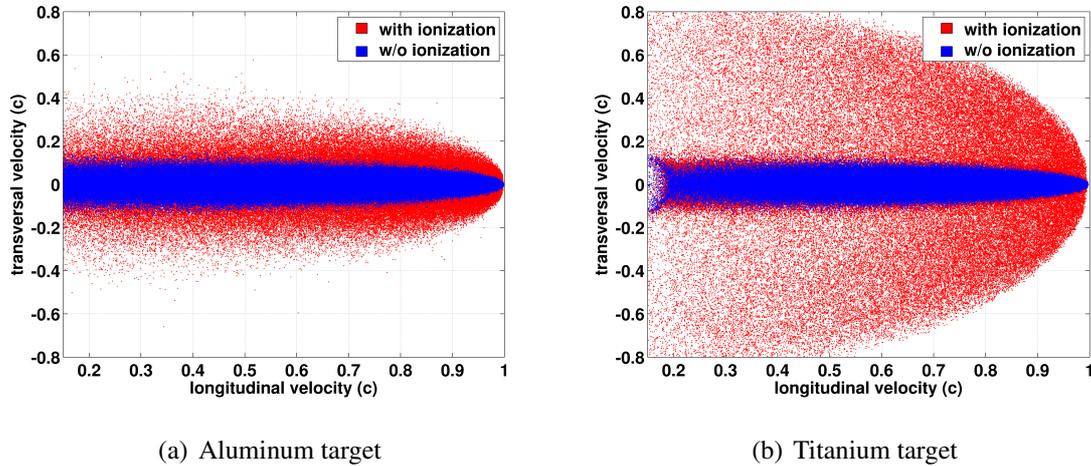

(a) Aluminum target   (b) Titanium target

Figure 2: The velocity phase space of electrons accelerated toward the target interior in PIC simulations with and without electric field ionization. The simulation parameters are given in the text. The red electrons lie also below the blue ones.

When the electrons that are displaced in the phase space, are accelerated toward the target, they keep a nonzero transversal velocity, which is similar to their initial transversal velocity displacement from the other plasma electrons. This results in a wider angular distribution of fast electrons in the laser electric field plane, as can be seen in Fig. 2 a). The blue electrons are accelerated toward the target in the simulation without variable ionization, the red ones in the simulation with ionization

Figure 3: Angular distribution of electrons accelerated toward the target in PIC simulations. The angle α is measured with respect to the target normal. Only electrons with energy above 100 keV are included.

(the red electrons lie also below the blue ones!). As we can distinguish, from which ionic shell electrons were released, we know that the electrons with the highest transversal velocity are coming from the inner aluminum shells (mostly 2s) near the laser pulse maximum.
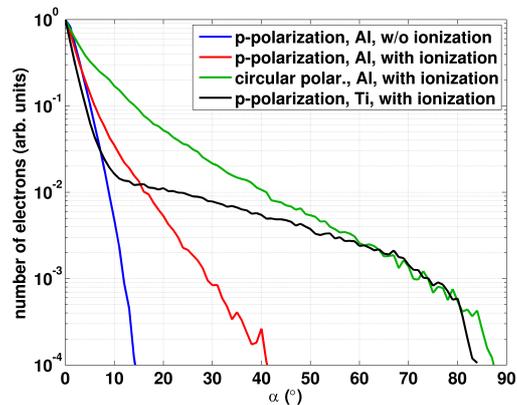
The wider angular spread of fast electrons, caused by the ionization of inner shell electrons, strongly depends on the laser parameters and the target material. In Fig. 2 b), we demonstrate the velocity phase space of accelerated electrons for the case of titanium target and the slightly longer 65 fs laser pulse with the same energy.

When the laser polarization is switched to circular, all the electrons released near the laser pulse maximum are displaced in the velocity phase space. In this case, the angular distribution of fast electrons is symmetrical cylindrically.

In Fig. 3, the angular distribution of accelerated electrons is demonstrated for both polarizations and target materials and compared to the distribution from the simulation without optical field ionization. The angle α is measured with respect to the target normal direction and the number of electrons is normalized. Only electrons with energy above 100 keV are included. For the titanium target 14% and for the circular polarization more than 20% of fast electrons are propagating outside the cone with an openning angle 30° around the target normal.

Finally, let us note that the effect of the optical field ionization on the energy distribution of accelerated electrons is not so significant. The fast electron temperature does not change and the overall efficiency of laser energy transformation into fast electrons is the nearly the same.

4. CONCLUSIONS

In this paper, we have demonstrated the effect of optical field ionization on the angular distribution of electrons accelerated toward the target in the interaction of short pulse high intensity laser with a solid target. Due to nonlinear effects in laser interaction with dense plasma, the electrons released from inner ionic shells by the field ionization in the underdense plasma are often displaced from other electrons in the velocity phase space. This results in wider angular spread of accelerated electrons and a less collimation of the fast electron beam. This effect strongly depends on the target material and laser parameters, particularly on the laser wave polarization.

References

[1] R. Lichters, R.E.W. Pfund and J. Meyer-ter-Vehn, Report MPQ **225**, Garching (1997).

[2] A.J. Kemp, R.E.W. Pfund and J. Meyer-ter-Vehn, Phys. Plasmas **11**, 5648 (2004).

[3] B. Penetrante and J. Bardsley, Phys. Rev. A **43**, 3100 (1991).

[4] S.X. Hu and A.F. Starace, Phys. Rev. Lett. **88**, 245003 (2002).