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Influence of Ionization on Fast Electron Beam Collimation in Short-Pulse High-Intensity Laser Target Interactions

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1. INTRODUCTION

Interactions of ultrashort intense laser pulses with solid targets are accompanied by efficient acceleration of dense relativistic electron beams. Acceleration and propagation of electron beams are extensively studied in connection with various applications, e.g. short X-ray pulses, ion acceleration, fast ignition. Most applications require electron beam with low angular divergence. Recent experiments demonstrated that angular distribution of accelerated electrons depends in particular on the acceleration mechanism [1]. Deflection of electrons accelerated into the target by the quasistatic magnetic field induced in plasma was observed in PIC simulations [2]. In this paper we demonstrate that the Optical Field Ionization (OFI) process taking place in the undercritical plasma may contribute to the angular divergence of the hot electron beam as well.

2. THEORY

The presented theory relies on high intensity laser solid target interactions. It is assumed that preplasma produced on the target surface by laser prepulses forms a relatively long (several λ) but only weakly ionized ($Z \leq 3$) density profile. In the underdense plasma new electrons are released mainly by the OFI during the interaction.

The OFI process is efficient when the local electric field amplitude is high, i.e. only around each maxima of the laser wave. Electric field of a plane harmonic laser wave with smooth envelope $E_0(t)$ reads $E(x,t) = E_0(t)\sin(\omega t - kx)$. In the field maximum, $\omega t - kx = \pi/2$, and the vector field potential, $A(t) \sim \int_{-\infty}^{t} E(x,t')\mathrm{d}t'$, is nearly zero. Free electrons, which were at rest before the interaction, have zero transverse momentum in the field maxima due to canonical momentum conservation. Newborn electrons released in the laser wave maxima have negligible energy upon ionization and they are in phase with other plasma electrons.

However, the field in the underdense plasma comprises of the incident laser wave and the wave specularlly reflected from the critical surface. The reflected wave may be phase shifted due to moving mirror effect and may consist of multiple harmonic waves with different wavelengths. The electric field in the underdense plasma is not harmonic, the condition $A \approx 0$ is not necessarily satisfied in the field maxima, and newborn electrons may be released out of phase with other plasma electrons. Newborn electrons have initially zero energy and if they are out of phase with the wave, they can absorb laser energy directly.

If the plasma field potential is neglected the ejection angle of electron accelerated by the plane laser wave into the target is described by [3]

$$\tan\theta = \pm\left[\frac{\gamma^2-1}{(\gamma\sin\alpha+C)^2}-1\right]^{-1/2}, \tag{1}$$

where θ and α are the electron ejection and the laser incidence angles, both measured with respect to the target normal, and γ is the relativistic factor of the ejected electron. The constant of electron motion C is written as $C = p_{\|}(t) + q/c\,A(t)\cos\alpha - \gamma(t)\sin\alpha$, where $p_{\|}$ is the component of the normalized electron kinetic momentum parallel to the target surface. For initially free and stationary electrons, $C = -\sin\alpha$, and the accelerated electrons are ejected into angle ranging between 0 and α depending on their final energy. For the newborn electrons released by OFI during the interaction, the constant of motion C may be different. Immediately upon ionization, the newborn electron is assumed to be at rest and the constant C can be found from the local instantaneous vector potential A. The constant of motion of the newborn electron can be written as $C = q/c\,A\cos\alpha - \sin\alpha$ and it should approximately lie in the interval $\pm a_0\cos\alpha - \sin\alpha$. Thus, only electrons born in the relativistic laser wave can be significantly dephased and they mostly originate from inner shells (e.g. 3s, 2p of Ti) as the outer shells are depleted at the beginning of the interaction. The above discussion applies to linearly polarized laser wave. In the case of circular polarization the OFI process is continuous and newborn electrons are always out of phase and ejected in different directions.

3. SIMULATION MODEL AND RESULTS

1D3V relativistic electromagnetic PIC code with variable plasma ionization is utilized to simulate interaction of an intense ultrashort laser pulse with preplasma on the target surface. Our code evolved from the code LPIC++ and it has been modified to account for electric field ionization using a Monte Carlo approach [4] with the ADK tunneling ionization rate. Energy spent in ionization is subtracted from the field by introducing artificial ionization current. Electrons released by ionization are injected into the simulation box with zero velocity.

Interaction of the linearly polarized, 40 fs long, laser wave with the wavelength 800 nm and maximum intensity of 10^{19} W/cm^2 with the solid target is studied. For the sake of simplicity normal incidence is assumed. The target consists of cold C, Al, or Ti plasma with relatively long ($L = 4\lambda$) exponential density profile on the surface. The simulations carried out with OFI assume initial ion charge 3. In the case of constant ionization $Z = 7$ (Ti).

The situation, when electron released by OFI is out of phase with other plasma electrons is demonstrated in Fig. 1. This figure depicts the electron phase space is one particular cell in PIC simulation with Ti target. In the case of normal incidence, canonical momentum conservation implies that the newborn electron keeps the transverse momentum (p_y) difference. In the presented case its ejection angle is 45° in contrast with nearly zero ejection angle of all other electrons.

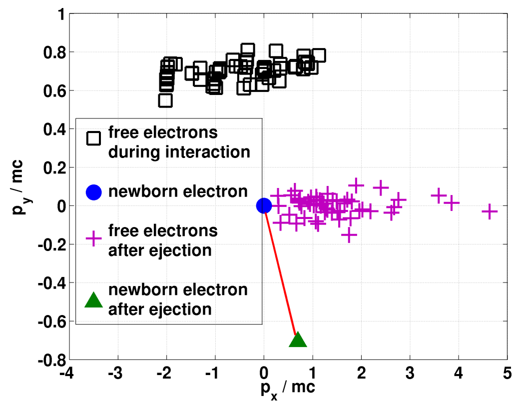
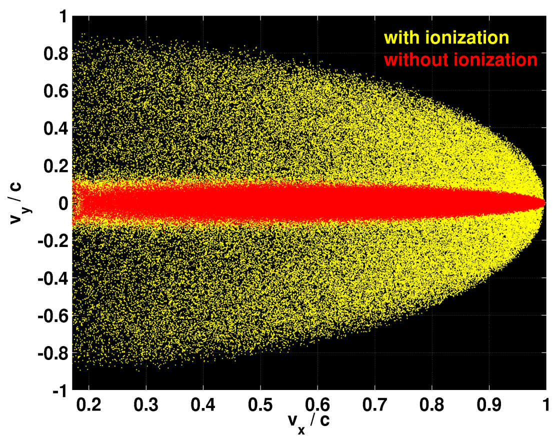
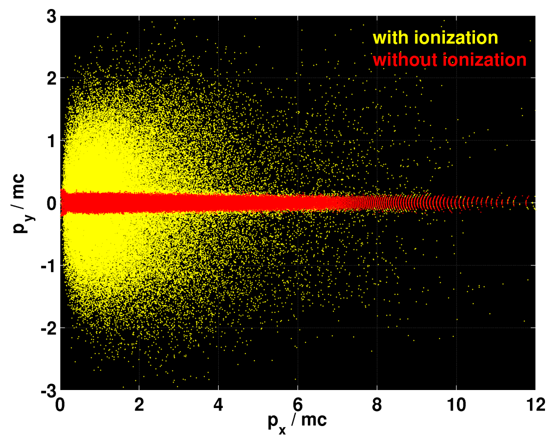


Figure 1: Electron momentum phase space in one undercritical simulation cells when new electron is just released by OFI. Final momentum of accelerated electrons is included for illustration. PIC simulation with Ti target and variable ionization.

The overall effect of OFI on the angular distribution of accelerated electrons is best seen in the velocity and momentum phase space plots presented in Fig. 2. In agreement with eq. (1) accelerated electrons propagate normally to the target surface in simulation with constant ionization. On the other hand, ejection angles of newborn electrons cover the whole range $(-\pi/2, \pi/2)$ and some electrons propagate almost along the target surface in the simulation with variable ionization. The pattern of accelerated electrons is symmetrical around $v_y = 0$ (v_y the velocity component along the target surface), ejection angles lie in the laser polarization plane. The high energy tail of hot electrons is better seen in the momentum distribution. The transverse momentum of newborn electrons is limited by the laser wave potential whereas the longitudinal momentum is determined by the acceleration process



(a) velocity phase space



(b) momentum phase space

Figure 2: Velocity and momentum phase space of electrons accelerated into the Ti target in PIC simulation with constant and variable ionization. 'Yellow' electrons lie bellow the 'red' ones!

and it can be much higher, i.e OFI does not influence propagation direction of the highest energy electrons significantly, which is in agreement with equation (1).

Angular distributions of accelerated electrons are demonstrated in Fig. 3 for both laser polarizations and target materials and compared to the distribution calculated without OFI. When OFI is taken into account the out of phase electron are responsible for the high ejection angle wings in the distributions. The effect of OFI increases with the ratio between the number of electron released by OFI from deeper lying shells and the total number of accelerated electrons, i.e. depends on the target material. For the Ti target about 14% of fast electrons propagate outside the cone with openning angle 30°. For higher Z targets and higher intensities, the number of dephased newborn electrons can be much higher, however we are not able to make these simulation due to computational reasons at this moment. Regarding the energy distribution of hot electrons, no significant effect of the OFI has not been observed.

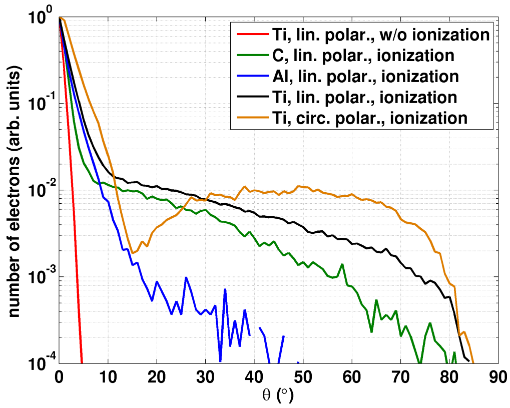


Figure 3: Angular distributions of hot electrons from PIC simulations with and without OFI and with different target materials. Electrons with $\gamma > 2$ are included.

4. CONCLUSIONS

We have demonstrated the effect of optical field ionization (OFI) on the angular distribution of electrons accelerated in the interaction of short intense laser pulse with solid target. Due to specular reflection of the incident laser wave, electric field in the underdense plasma is not harmonic and electrons released in the field maxima by the OFI of deeper lying shells are significantly dephased from other plasma electrons. This results in wider angular spread of accelerated electrons and less collimation of the fast electron beam. The presented effect strongly depends on the target material and laser parameters, particularly on the laser wave polarization.

Acknowledgments

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