Lateral hot electron transport and ion acceleration in femtosecond laser pulse interaction with thin foils

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Abstract. In this paper, the lateral electron transport in a thin foil, limited in transverse sizes, is studied by numerical PIC simulations for two linear polarizations (p, s) of femtosecond laser pulse incident on a foil at various angles. The transport is due to hot electron recirculation forth and back and electron guiding on the foil surface by quasi-static magnetic and electric fields. It is demonstrated that the second mechanism takes place for larger incidence angles, although the recirculation is still important. There, ions accelerated from a lateral foil edge, which is out of the laser focal spot, can have higher energies than the ions from the rear foil side.

1. Introduction

Lateral electron transport in thin foils is a result of two phenomena. The first one is a fast electron current propagating along the target surface revealed in recent theoretical analysis, numerical simulations, and experiments [1], [2]. This current is generated by a short laser pulse of a relativistic intensity ($I \lambda^2 \approx 10^{19}$ Wcm$^{-2}$µm$^2$) when it is incident on a plane target at a large angle ($\theta \approx 70^\circ$). Generated strong quasi-static magnetic and electric fields confine electrons in a potential well along the target surface and the electrons are resonantly accelerated by laser electric field inside the potential well [3]. This could result in electron energies exceeding ponderomotive potential and in transport of those electrons along the target surface far beyond interaction region.

The second mechanism of the lateral electron transport is due to hot electron recirculation. In this case, most of accelerated electrons pass through the target and are reflected in the expanding Debye sheath on the rear surface. This results in reversing of the normal component of electron velocity while the transverse velocity is largely unaltered. Hot electrons reflux in the foil many times and propagate towards target edges. The resulting ion emission from the edges of thin target foil or from moving electron sheath towards the foil edge, was investigated in Ref. [4] and Ref. [5], respectively.

In this paper, we investigate the influence of these two mechanisms on fast electron transport towards foil edges and on resulting ion acceleration. We performed 2D PIC simulations of the interaction of femtosecond laser pulse with an ionized thin foil target and studied the dependence of the electron lateral transport on the laser incidence angle. The latter is also quantified by analysis of characteristics of fast protons emitted from foil edges.
2. Simulation method and parameters

Our relativistic collisionless particle-in-cell (PIC) code in two spatial directions and with three velocity components is described in Ref. [6]. To investigate the lateral electron transport itself and its effect on proton acceleration, several simulation setups were chosen. The incidence angles of 30°, 45°, 60°, and 75° were considered for both $p$ and $s$ polarizations of the laser beam. Other simulation parameters are similar for all runs.

A fully ionized foil of the size $77\lambda \times 2\lambda$, consists of electrons and protons of the initial density $20\, n_c$ (where $n_c$ is the electron critical density). The transverse foil size is set to be two times larger than the laser focal spot for the largest incidence angle, i.e., $(10\lambda/\cos 75^\circ) \times 2 = 77\lambda$, in order to observe the lateral transport and dissipation of surface electron current outside the interaction zone. A laser beam at the wavelength $\lambda = 1.0\, \mu m$ has a super-Gaussian profile ($n=5$) in the perpendicular plane with the width $10\lambda$ at half maximum. The temporal laser pulse profile has a trapezoidal shape with a constant maximum intensity $3.4 \times 10^{19}\, W/cm^2$ (the dimensionless amplitude $a_0 = 5.0$) of duration $20\tau$ (in laser periods, 67 fs), and two linear ramps of duration $5\tau$ (17 fs) at the beginning and at the end of the pulse.

3. Results and discussion

In the case of $p$-polarization, our simulations with large laser pulse incidence angles (75° and 60°) show that some electrons are pulled out from the target front by the electric field of the laser wave and their trajectories are bent parallel to the surface by the magnetic field of the wave. A part of those ejected electrons is pulled back into the target, but some of them rest close to the target front and form a bunch which moves along the surface in the direction of incident laser wave vector projection onto the foil. The fast electrons are moving outside the target while the return current is flowing in a dense plasma at the target surface. The bunches are distributed regularly with $\lambda/\sin(\theta)$ interval. That indicates that the Brunel absorption mechanism dominates in this case.

In the case of $s$-polarization, the oscillating electric field is parallel to the foil surface and perpendicular to the simulation plane, the electrons cannot be pulled out from plasma directly by the electric component of the laser wave, but they can be ejected by $j \times B$ heating. Therefore, the bunches of electrons are ejected twice per laser period and are distributed regularly with $\lambda/\sin(2\theta)$ interval. Thus, the period is twice shorter and the maximal current is smaller compared with the $p$-polarization case.

Fig. 1 shows averaged densities of the most energetic electrons (their kinetic energy is higher than 3 MeV) on the front foil surface for both laser beam polarizations and for incidence angle of 75°. The densities are calculated in two surface regions of sizes $4\lambda \times 1.5\lambda$ - ”region 1” is located at the laser focal spot and ”region 2” outside the spot region. In the region 1, one can see electron bunches moving along the foil surface with the velocity close to $c$ as it was discussed above. Outside the spot region (region 2), accelerated bunches of electrons are gradually broadened into continuous electron current and dissipated, more rapidly in the case of $s$-polarization.

We also analyzed electron energy spectra on the foil front surface in both regions. For larger incidence angles (75° and 60°), the spectra contain a high energy tail. The energy of electrons in this tail is much higher than the value of ponderomotive energy $\varepsilon_{eh} \approx m_ec^2(\sqrt{1 + a_0^2}/2 - 1) \approx 1.5\, MeV$. Such spectra are in agreement with simulations in Ref. [3]. That confirms that the surface acceleration takes place in the laser irradiated zone. The physical mechanism of electron surface acceleration is rather similar to the betatron acceleration in laser channels [7], [8].

In order to assess the influence of lateral hot electron transport on ion acceleration, we compare fast ion characteristics in simulations with four laser beam incidence angles (30°, 45°, 60°, 75°). Dependencies of maximum proton energy $\varepsilon_{imax}$ and ion energy fluence $W_{int}$ (that is, the total energy of ions accelerated from a unit surface) on the incidence angle are shown in Fig. 2. These values are calculated from spectra ”measured” in the strip of width $1.75\lambda,$
Figure 1. Density of hot electrons along the target front in two time instants in surface regions 1 and 2 (incidence angle of 75°). Only electrons with energy higher than 3 MeV are taken into account. The first region is located in the center of interaction zone. The second region is shifted along the front surface 30λ to the lateral right side and recorded about 30τ later than the first, which corresponds to the shortest time needed for electrons to be moved from the first to the second region. The regions are located from \(y = -1.0\lambda\) to \(y = 0.5\lambda\), initial plasma-vacuum interface at \(y = 0\).

Figure 2. Left panel - Dependence of maximum energies of protons on the position of the emission zone on the target and the incidence angle: 1 - middle front, 2 - middle rear, 3 - lateral right, 4 - lateral right, s-polarization, 5 - lateral right r.b.c., 6 - lateral left; "r.b.c." denotes the simulation cases where the fast electrons escaping to vacuum are replaced by thermal electrons of Maxwellian distribution with initial temperature about 1 keV; all the lines except for line 4 are related to p-polarized laser pulse.

Right panel - Energy fluences of protons emitted from different target regions for incidence angles of 30°, 45°, 60°, and 75°. Only protons with kinetic energy higher than 1 MeV are taken into account. Line numbering has the same meaning.

perpendicular to the surface in the center of foil on its front, rear sides, and on lateral sides at the time of 250 fs after the interaction of the laser pulse with the target, when the ion acceleration process is terminated. The acceleration from left side is relatively weak and decreases with increasing incidence angle as the hot electrons are mostly accelerated in the direction of the laser wave vector projection onto the foil surface towards lateral right side. There, a strong proton acceleration takes place for large angles.

The maximum proton energy on lateral right side is 27 MeV and 29 MeV and the corresponding ion energy fluence about 21 kJ/cm² for p-polarization and 16 kJ/cm² for s-
polarization, respectively, in comparison with the energy fluence of laser pulse about 2.8 MJ/cm². The number of accelerated ions is higher for the p-polarization in spite of a stronger confinement of absorbed laser energy in the case of s-polarized pulse. This fact can be explained by the electron energy distribution which is not favorable for an efficient proton acceleration in the case of s-polarization, because it is dominated by a relatively small number of fast electrons. These most energetic electrons overcome the potential barrier created by the ions and by themselves, and are lost from the system (they are accumulated on the boundaries of the simulation box), whereas less energetic "bound" electrons participate in the acceleration, according to a theoretical model of Ref. [9].

In the case of p-polarization, additional simulations were performed to demonstrate explicitly the effect of electron surface guiding on proton acceleration. The runs where hot electron recirculation is artificially suppressed shows that the recirculating electrons (which are mostly observed in the p-polarization case) contribute significantly to proton acceleration, even for the largest incidence angle. A significant difference between a standard simulation and the run with the substitution of hot by thermal electrons on the rear foil side can be observed, both, in the cutoff energy and in the energy fluence related to the lateral right foil side. The difference is more pronounced in the proton energy fluence as the most energetic electrons guided along the surface (which are presented in all simulations) enhance mainly the cutoff energy, whereas recirculating electrons (less energetic, but more numerous) are contributing into the enhancement of the fluence (as it depends more strongly on hot electron density).

4. Conclusion

Lateral electron transport in a thin foil due to hot electron guiding along the foil front surface is investigated by 2D PIC simulations. While a femtosecond laser pulse is incident on the foil with a large angle (more than 60°), a part of electrons is confined on the foil front. They are accelerated to very high energies exceeding the ponderomotive energy, and transported towards an edge of the foil in the direction of laser wave vector projection onto the foil front surface. The ions emitted from the foil edge (lateral side), which is out of the interaction region, by the electric field created by these electrons can reach even several times higher maximum energy than the ions accelerated from the rear foil surface in the target center, although their total number is rather low. These guiding and acceleration effects are not observed for smaller incidence angles. In this case, the lateral transport is mainly due to multiple recirculation of electrons through the foil and the energies of transported electrons are much lower.

To clearly observe the effect of the electron guiding along foil front surface on proton acceleration, an artificial boundary condition cooling down recirculated electrons is applied on the rear foil surface. It is shown that hot electron recirculation forth and back still plays an important role even for very large incidence angles, which are considered for the cone targets used for fast ignition. Therefore, the schemes that reduce losses of recirculating electrons along the cone wall would increase the electron transport efficiency.

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