

RELATIVISTIC SHORT-PULSE LASER INTERACTION WITH THIN FOILS

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Abstract. Using 2d particle-in-cell (PIC) simulations we investigate generation of fast particles in an intense high-contrast laser interaction with thin overdense plasma targets for an oblique p -polarized laser incidence.

1. INTRODUCTION

Following advances in high-power laser technology significant theoretical and experimental efforts have been directed toward production of high-energy high-quality particle beams from the laser-plasma interaction. Intense multi-MeV proton beams have been routinely obtained in experiments (Zepf et al. 2003, Fuchs et al. 2005) from both, the front and rear surface of the solid foils and supported by computer simulations (Sentoku et al. 2003, D'Humières et al. 2005). Since the high energy ions cannot be directly accelerated by the laser fields used in current experiments, the electron dynamics plays a crucial role in the energy transfer from the laser beam to the ions. Over past years several mechanisms of the ion acceleration have been proposed (see e.g. Habara et al. 2004), and it is widely accepted that the charge displacement due to the electron heating at the front surface of the target and formation of electrostatic sheaths can be the driving force for the ion acceleration. However, theoretical and simulation predictions are not often in agreement with experimental results.

Using two-dimensional (2d) PIC simulations we address the generation and transport of fast electrons in a high-contrast short-pulse laser interaction with thin targets, identifying electron recirculation and drift from the focal region. In particular, we consider the interaction of an intense laser light with thin overdense plasma foils for an oblique wave incidence.

2. SIMULATION RESULTS

In order to investigate the generation and transport of energetic particles in the laser-plasma interaction, a series of 2d relativistic electromagnetic (EM) PIC simulations with absorbing boundaries was carried out. A linearly p -polarized (along y -axis) laser beam was injected from the left boundary of the simulation box in x -direction and focused onto overdense plasma targets. The time and space profile of the laser beam was Gaussian with a full width at half maximum (FWHM) duration of 40fs ($\approx 30T$ for $\lambda = 0.4\mu\text{m}$), the diameter of the focal laser spot was $2.4\mu\text{m}$, and the laser strength at the peak was $a_0 = eE_0/(mc\omega_0) = 0.7$ (for $\lambda = 0.4\mu\text{m}$, the laser intensity is $I \approx 4.2 \times 10^{18} \text{ W/cm}^2$). Here T denotes laser wave period, λ is the laser wavelength, E_0 is the laser electric field amplitude, c is the speed of light, ω_0 is the laser frequency, and e and m are the electron charge and mass, respectively. In the simulations 50 particles per species per cell were used with 40 cells/ λ , and the initial electron temperature was $T_e < 4\text{keV}$.

In the focus of our attention here is the interaction of the oblique laser beam with an electron-proton plasma foil at an angle of incidence of $\alpha = 45^\circ$. The foil thickness in this case is $L = 2.5\mu\text{m}$ (6.25λ) and the density is $n = 10n_{\text{cr}}$, where n_{cr} is the critical (cutoff) density. In the simulations the time $t/T = 0$ was set to the peak intensity of the laser beam at the focal spot with the center at $(x/\lambda, y/\lambda) = (0, 0)$.

The simulation results reveal that for parameters considered here, a majority of electrons are accelerated in directions between the normal to the plasma surface and the laser beam axis, with the hot electron population directed more towards laser beam axis. Reflection of electron clouds from the edges of the foil and their recirculation is a striking effect that is characterized by the breaking of the transversal symmetry (in respect to the laser beam axis) of the fast electron flow. Namely, it is found that the fast electrons quickly leave the interaction region drifting along the foil. We illustrate this effect by Fig. 1 where we plot snapshots of the electrons with $E > 1\text{MeV}$ at $t/T = -0.6$ (Fig. 1a), and $t/T = 27.6$ (Fig. 1b). As one can see (Fig. 1a), well defined bunches of the fast electrons (low energetic electrons in the background are not shown) generated at each wave cycle propagate in the forward direction. The electric fields established by the charge separation reflect these electrons back and forth with an effective drift along the foil in the laser beam direction (see Fig. 2). Due to the different velocity of the electron bunches, these electron structures gradually disappear during the propagation (see Fig. 1b). Since the low energy electrons are generated more in the normal direction to the target surface, they recirculate in the focal region and interact multiple times with the laser wave. This electron interaction dynamics can play an important role in increasing proton energies. Here, we found that at $t/T = 63$ the maximum ion energies are $E_f \approx 1.38\text{MeV}$ and $E_b \approx 1.70\text{MeV}$ in the forward and backward direction, respectively. As we can see, the energy of the backward accelerated ions exceeds the energy of the forward propagating ions. This can be explained by the fact that the charge separation induced on the front surface due to the electron circulation back and forth is well enhanced by significant ejection of the electrons in the backward

direction. Moreover, in favor of efficient backward ion acceleration is also the fact that the front surface is sharp edged allowing strong field gradients.

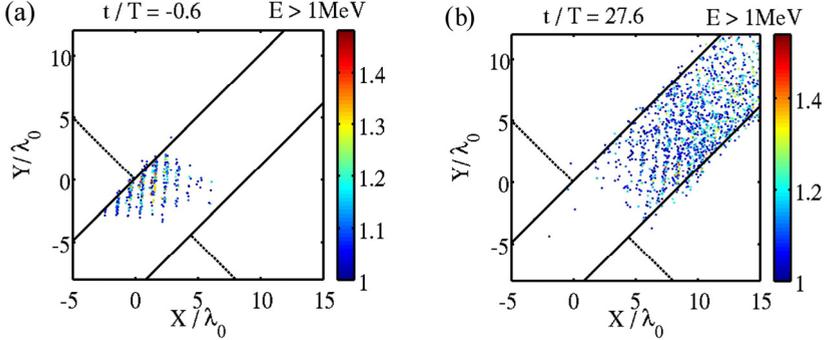


Figure 1: Snapshots of fast electrons with $E > 1\text{MeV}$ in space at (a) $t/T = -0.6$, and (b) $t/T = 27.6$, in the oblique laser interaction with the foil. Full and dashed lines denote initial plasma boundaries and the normal to the plasma interface at the center of the focal spot, respectively.

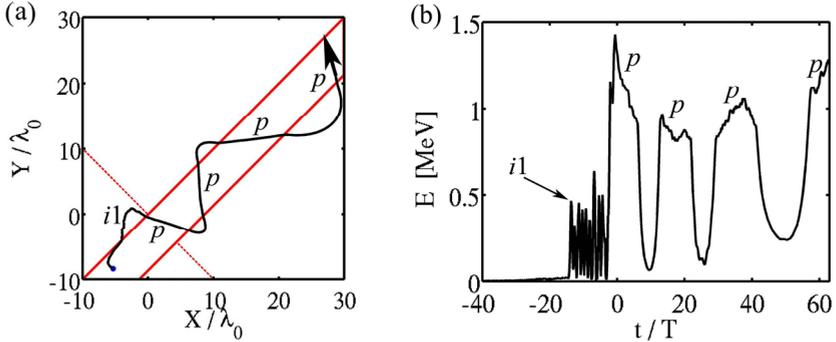


Figure 2: (a) Trajectory of the test electron and (b) its energy history in the laser-foil interaction. *il* denotes laser-electron interaction, while *p* denotes electron motion in the plasma. The full and dashed lines show initial plasma boundaries and the normal to the plasma surface at the focal spot, respectively.

It is found that the dominant mechanism of the ion acceleration in our simulations is target normal sheath acceleration (TNSA), and no significant presence of other mechanisms is seen. To confirm previous conclusions, a long run with the same laser-plasma conditions but with the laser pulse duration of 80fs has been carried out. In Fig. 3 we plot space distribution of protons with $E > 1\text{MeV}$ from this run at $t/T = 25.9$ (Fig. 3a) and $t/T = 237.3$ (Fig. 3b). In Fig. 3a one can see the core of the accelerated ion beams normal to the foil surfaces with a small shift in respect to the target normal at the center of the focal spot. This shift is more pronounced for forward propagating proton beam reflecting the fact that the bulk of electrons is accelerated in direction between the target normal and the laser beam axes. The proton beam shift is preserved at later times, however due to the creation of the low energy proton wings in the preferred direction of the fast electron

flow, the beams exhibit transversal asymmetry (see Fig. 3b). Although the ion energy stabilization can take place on picoseconds scale it is clear that the backward proton beam keeps an advantage in higher proton energy. The fact that the fast electrons have preferred flow that depends on the laser incidence and the target geometry has important consequences on particle dynamics in more complex targets (e.g. cone target) in today's experiments on fast ignition (Nikolić *et al.* 2008).

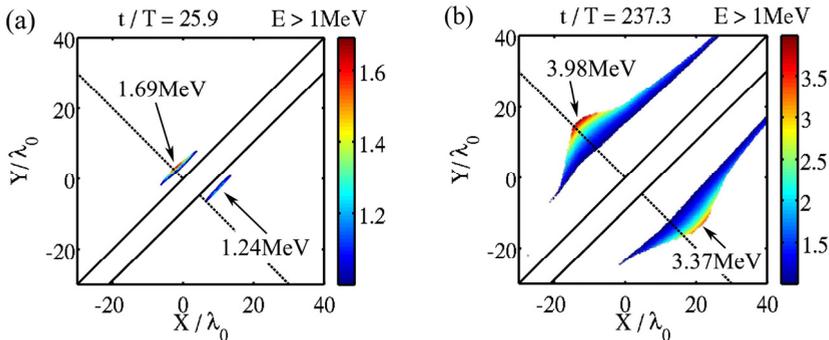


Figure 3: Space distribution of protons with energies $E > 1 \text{ MeV}$ at (a) $t/T = 25.9$ and (b) $t/T = 237.3$. Full and dashed lines denote initial plasma and the normal to the plasma surface at the center of the focal spot.

3. SUMMARY

Simulation results reveal that electron reflections from the target surfaces is a streaking effect in the interaction of intense laser light with thin plasma foils. While the low energy electron population can circulate in the focal region for a longer time, a large number of fast electrons quickly drift away from the interaction region. The drift of electrons in a preferred direction induces long tails of low energy protons. This suggests that in more complex target geometries the organized electron flow may produce parasitic ions far from the focal spot.

Acknowledgements

Partial support by the Ministry of Sciences and Technology of Republic of Serbia, Project 141034, are gratefully acknowledged.

References

- D'Humières, E. *et al.*: 2005, *Phys. Plasmas*, **12**, 062704.
 Fuchs, J. *et al.*: 2005, *Phys. Rev. Lett.*, **94**, 045004.
 Habara, H. *et al.*: 2004, *Phys. Rev. E*, **69**, 036407.
 Nikolić, Lj. *et al.*: 2008, *Journal of Physics*, **112**, 022086.
 Sentoku, Y., Cowan, T. E., Kemp, A. and Ruhl, H.: 2003, *Phys. Plasmas*, **10**, 2009.
 Zepf, M. *et al.*: 2003, *Phys. Rev. Lett.*, **6**, 064801.