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Acceleration of ions from ultrathin foils driven by short intense high-contrast laser pulses

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1. INTRODUCTION

Interaction of an ultra-short intense laser pulse with a target results in heating and acceleration of electrons. Their subsequent expansion from the target surface is accompanied by Target Normal Sheath Acceleration (TNSA) of ions. Energetic ions accelerated from thin foil targets by short intense laser pulses are interesting for various applications, e.g. radiography, isotope production, isochoric heating [1]. However, it is desirable to increase the efficiency of the ion acceleration process and the maximum ion energy. As demonstrated in recent experiments [2], the maximum ion energy can be increased by decreasing the foil thickness and using a high contrast laser pulse to avoid premature disruption of the foil by laser prepulses. However, absorption of energy of an ultra-short prepulse-free intense laser pulse on the flat foil surface (free of preplasma) may be relatively low especially at normal incidence. The laser energy absorption is higher when the pulse is incident obliquely but on the other hand the laser pulse intensity on the target surface (and hence also the maximum ion energy) is reduced in this case.

The laser energy absorption may be boosted by the presence of microscopic structures on the laser irradiated target surface as demonstrated in recent experiments (e.g. with polystyrene microspheres [3]). Recently, such targets have been used to study ion acceleration by short intense laser pulses [4] but with no evidence for the maximum ion energy increase. However, the target used in the experiment was relatively thick so that recirculation of hot electrons could not be efficient and the accelerated ions have been recorded at the front side. Recently, a monolayer of polystyrene spheres with 800 nm in diameter has successfully been deposited on a 700 nm thick plastic foil in our institute [5]. This target enables to benefit from both higher absorption and efficient hot electron recirculation and it is thus suitable for efficient ion acceleration. Ion acceleration by short intense laser pulses from thin foils covered by a monolayer of microspheres or foils with a kind of surface grating is studied in this paper using 2D PIC simulations.

2. SIMULATION MODEL AND RESULTS

The 2D simulations have been performed with our relativistic electromagnetic parallel PIC code [6]. The targets used in our simulations consist of 200 nm thick foil, with and without a

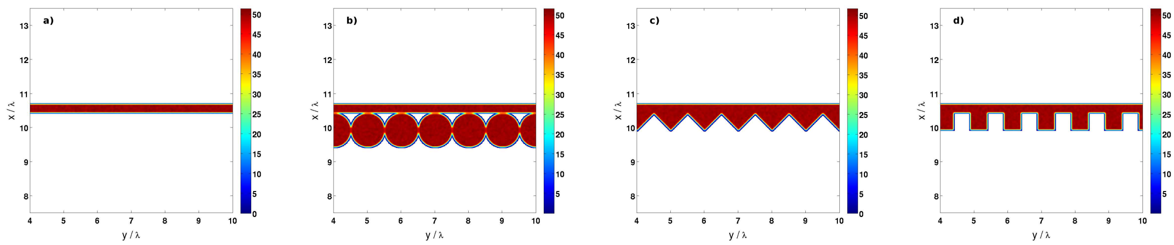

Figure 1: The structure of targets used in our 2D PIC simulations. The initial free electron density (represented by the color) in the target is plotted in the units of critical density. The laser pulse (with the wavelength λ) is incident from the bottom.

kind of periodic surface structure attached to the front side (see Fig. 1). The shape of the structure is spherical, rectangular or triangular. The target consists of 2 species of ions (homogeneous 1:1 mixture of C^{4+} and protons) and free electrons with the initial density of 50$\times$ critical density. The initial temperature is very low ($\approx$ 10 eV) to avoid preexpansion of the target prior to the laser pulse arrival. The 20 fs long p-polarized laser pulse with the wavelength 800 nm and the maximum intensity of 1.7×10^{19} W/cm^2 is used in these simulations.

In the first simulations, we have compared the interaction of the laser pulse with the targets plotted in Fig. 1. The results of these simulations are summarized in Table 1 and they indicate that the surface structures boost the laser energy absorption and the maximum ion energy. In the case of flat foil surface, the temperature and the number of hot electrons are much lower but on the other hand, hot electrons propagate in a collimated beam. The structures on the target surface cause higher absorption but the hot electron beam is very divergent. Therefore, the increase in the maximum proton energy is not so big. Nevertheless, the energy transformation efficiency into fast protons scales almost linearly with laser absorption in our collisionless simulations.

target	electron temperature	electron divergence	absorption	max. proton energy
a)	0.10 MeV	14.8°	3.8%	0.85 MeV (0.88%)
b)	0.40 MeV	39.7°	55.2%	3.76 MeV (7.3%)
c)	0.42 MeV	41.8°	80.5%	4.85 MeV (11.3%)
d)	0.37 MeV	40.9°	43.9 %	3.73 MeV (5.0%)

Table 1: Comparison of the results of PIC simulations with the targets plotted in Fig. 1. The parameters of hot electrons are measured after the end of the laser target interaction, those of protons at the end of simulations ($\approx$ 300 fs). The electron divergence is the average angle of electrons with $E > mc^2$ with respect to the target normal. The transformation efficiency of the laser energy into the fast protons is in the parenthesis next to the max. proton energy.

The electron and the proton energy distributions resulting from PIC simulations with flat foil surface and with microspheres on the surface are plotted in Fig. 2. The structure of the energy distribution of protons (the peak and the dip) comes from their interaction with fast C^{4+} ions as described in [7]. The structure is not significant in the case of protons accelerated from the flat foil as the C^{4+} ions are not significantly accelerated in this case.

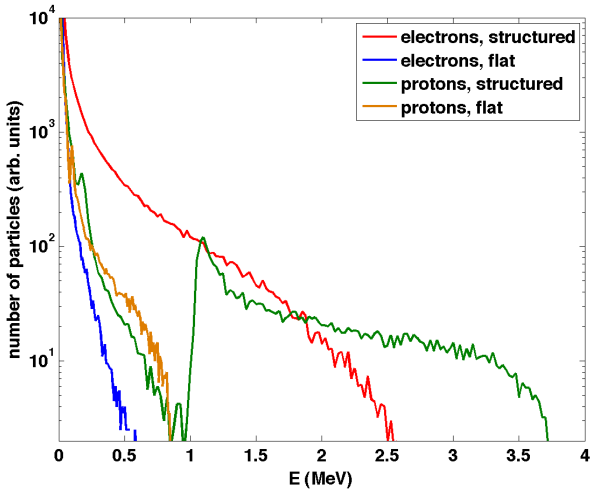

Figure 2: Electron and proton energy distributions resulting from PIC simulations with flat foil surface and with microspheres on the surface. Electrons after the end of the laser target interaction, protons at the end of simulations (≈ 300 fs).

In the next series of simulations, we have concentrated on the target with a monolayer of spheres on the surface. The structure on the surface of the target has one degree of freedom in this case - the sphere diameter, and this parameter is changed in our simulations to maximize the energy of accelerated protons. The results of this optimization are summarized in Fig. 3.

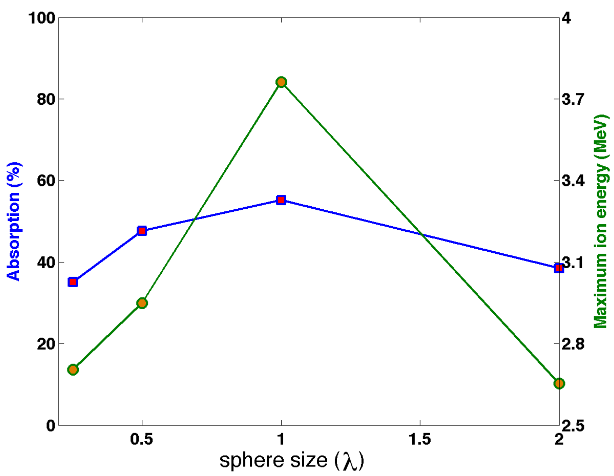

Figure 3: The dependence of laser energy absorption and of the maximum ion energy on the diameter of spheres in the monolayer on the surface of the foil.

As can be seen in Fig. 3, the maximum absorption and the maximum energy of accelerated protons approximately coincide when the diameter of spheres in the monolayer on the target surface is about the laser wavelength. From the experimental point of view, it might be difficult to prepare a homogeneous monolayer of mircospheres, all of the same size. We have performed an additional simulation with the spheres of random diameter, which is in the range $0.25-1\ \lambda$ and the resulting absorption of 57% and the maximum proton energy of 3.74 MeV are even slightly higher than in the best case of Fig. 3.

We have also investigated the influence of the structure size and its height on laser absorption and ion acceleration for the case of surface gratings (see Fig. 1 d). The simulations performed with the grating with double spatial frequency and rectangular structure (i.e. size of structures

$\frac{1}{4}\,\lambda \times \frac{1}{2}\,\lambda$) give 64% absorption and 4 MeV protons (note that the areal density is conserved). These results are particularly interesting, because from the geometrical point of view, one may expect that the absorption would be lower than 50%, as this is the area occupied by the front surface of the grating, where the absorption is expected to be negligible. The results indicate that such simple point of view is not satisfactory. Another interesting result has been obtained when the height of the structure has been increased 2× (i.e. size in the y direction of $\frac{1}{4}\,\lambda$ and height of λ). The laser energy absorption in this case is even higher 76%, but the maximum proton energy is only 3.5 MeV. This indicates that when the height of the surface structure is increased the absorption gets higher. However, this conclusion cannot be extended to the maximum ion energy. The surface structure expands very rapidly after the end of the laser target interaction and it contributes to the thickness of the target reducing the efficiency of the electron recirculation process. Thus there exists some optimum height of the structure for ion acceleration, where the absorption is high and the electron recirculation process is efficient.

4. CONCLUSIONS

In this paper, we study target normal sheath acceleration of ions from thin foil targets with flat or structured front surface using 2D PIC simulations. The structure on the front surface significantly increases laser energy absorption and hot electron temperature and density. This results in higher ion acceleration efficiency and maximum ion energy in the case of thin foil targets used in this paper. The ion acceleration process depends on the shape and size of the structure on the surface. The maximum ion energy is obtained for such characteristic dimensions of the structure for which the absorption is high and the electron recirculation process is efficient.

Acknowledgments

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