Short pulse laser interaction with micro-structured targets: simulations of laser absorption and ion acceleration

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**Abstract.** The interaction of an ultrashort intense laser pulse with thin foil targets is accompanied by the acceleration of ions from the target surface. To make this ion source suitable for application, it is of particular importance to increase the efficiency of laser energy transformation into accelerated ions and the maximum ion energy. This can be achieved by using a thin foil target with a microscopic structure on the front, laser-irradiated surface. The influence of the microscopic structure on the target surface on the laser target interaction and subsequent ion acceleration is studied here using numerical simulations. The influence of the shape and size of the microstructure, the density profile and the laser pulse incidence angle is also studied. Based on the simulation results, we propose to construct the target for ion acceleration experiments by depositing a monolayer of polystyrene microspheres of a size similar to the laser wavelength on the front surface of a thin foil.

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1. Introduction

The interaction of an ultrashort intense laser pulse with a solid target is accompanied by the heating and acceleration of electrons. Their subsequent expansion from the target surface leads to space-charge separation, which is accompanied by the generation of a strong quasi-static electric field in the sheath on the target surface. This self-induced field decelerates expanding electrons and accelerates ions from the target surface into vacuum. The whole process is known as target normal sheath acceleration (TNSA) [1]–[3]. Laser-irradiated targets can thus serve as microscopic and intense sources of short pulses of ions, which are synchronized with the laser beam itself. The ions accelerated from the target surface in the TNSA process form a collimated beam with high laminarity [4, 5]. Such properties make them interesting for various applications, such as proton imaging, isochoric heating and warm dense matter, and for applications where energy deposition in a small volume inside an irradiated object is desired [6]. For most applications, however, it is necessary to increase the energy transformation efficiency into fast ions as well as their maximum and characteristic energy.

It has been demonstrated in recent experiments that the maximum proton energy as well as the energy transformation efficiency into accelerated protons can be increased by reducing the thickness [7] and lateral dimensions [8] of the target. This increase is caused by a higher surface-to-volume ratio, which makes hot electron refluxing more efficient and induces a situation such that hot electrons spend a great deal of their energy at the target surface to support the electrostatic field, which accelerates ions. However, targets with reduced dimensions, especially thickness, i.e. ultrathin foils, must be irradiated by high-contrast, prepulse-free laser pulses to avoid their premature disruption, which may otherwise reduce the efficiency of the TNSA process [9, 10].

The contrast of laser pulses has recently been increased by almost four orders of magnitude using, for instance, a double plasma mirror (DPM) [11]. A short high-contrast laser pulse with peak intensity \( \lesssim 10^{20} \text{W cm}^{-2} \) reflected from the DPM contains a relatively very small amount of energy in the ns and ps pedestal and thus the target is almost intact until the beginning of the interaction with the main laser pulse. At the same time, the plasma created on the target surface by the rising edge of a short main laser pulse does not have enough time to expand and the density profile on the surface is thus very steep during the interaction. The absence of a plasma
density profile may have a detrimental effect on laser absorption, especially at normal incidence and if the target surface is very flat. The laser energy absorption may be substantially increased when the pulse is incident obliquely. Nevertheless, most of the laser pulse energy is reflected even in this case. Moreover, the maximum intensity of an obliquely incident laser pulse in the focal spot on the target is decreased and the angular divergence of accelerated electrons may be increased. This may also have a negative effect on the acceleration of ions from the target surface.

The laser energy absorption may be boosted by the presence of microscopic structures on the laser-irradiated target surface, as demonstrated in recent experiments [12]–[19] and simulations [20]–[24]. Such targets have been widely used to increase the transformation efficiency of laser energy into x-ray emission [14, 16, 18, 19]. Recently, bulk Cu targets with nano-structures on the surface have also been used to study ion acceleration include by short intense laser pulses from the front, laser-irradiated target surface [25, 26]. In spite of the enhancement in the hard x-ray emission and in the flux of moderate energy ions owing to the presence of nano-particles on the surface, this experiment demonstrated that nano-particles reduce the maximum ion energy. However, the average size of nano-particles on the target surface was only 15 nm and the thickness of the layer containing these particles was about 0.2 µm. In such a case, the intensity contrast ratio of $10^{-6}$ may be insufficient for the main laser pulse intensity higher than $10^{16}$ W cm$^{-2}$, and it is not clear whether the nano-particles survive throughout the main laser pulse interaction [27]. Therefore, the results on the influence of surface structure on ion acceleration may not be conclusive. In contrast, according to PIC simulations [28], the presence of surface micro-structure (the size of particles is now comparable to the wavelength of the laser pulse) significantly increases the energy of the ions emitted from the rear side of the target if the target is thin enough and the laser contrast is sufficiently high.

As a consequence, a target with reduced dimensions and a micro-structure on the surface may benefit from both higher absorption and efficient hot electron refluxing; thus it is suitable for an efficient ion acceleration induced by ultra-short ultra-intense and high-contrast laser pulses. As will be shown in this paper, a suitable candidate for such a target may be a thin foil covered by a monolayer of polystyrene spheres with diameters of the order of the laser wavelength.

The interaction of short intense laser pulses with a target with or without a micro-structure on the laser-irradiated surface is studied in this paper using particle-in-cell (PIC) simulations. The simulation model is described in section 2. The dependence of laser energy absorption on the shape of the surface structure and on the size of the structure in the case of microspheres is studied in section 3. The influence of the enhanced absorption due to the presence of a micro-structure on the acceleration of ions from the target surface is also demonstrated and discussed. In section 3, it is also shown that the same result can be obtained even if the surface structure is irregular to some degree. The conversion efficiencies and maximum energies of fast protons are calculated for both normal (or near normal) and oblique incidence of the p-polarized laser pulse and are compared with the results calculated for the flat foil surface in section 4. The parameters of the laser pulse and of the foil better correspond to what is used in current ion acceleration experiments at Ti : sapphire laser systems with a power of several TW. The influence of a finite laser prepulse is also described. Ion acceleration from the front side of a bulk target in the backward direction (opposite to the laser incidence direction) is also discussed. In section 5, we summarize the most important results and present our concluding remarks.
2. Simulation model

Numerical simulations of the short intense laser pulse interactions with foil targets and of the subsequent ion acceleration are performed using our two-dimensional (2D) PIC code [29]. The code is relativistic and electromagnetic and takes into account all three components of particle velocities and electric and magnetic fields (2D3V). The relativistic equations of motion are solved by the two-step Boris algorithm and the fields in the positions of particles are determined by bilinear interpolation. The zigzag scheme [30] is employed for the calculation of current densities in order to guarantee an automatic compliance with the discrete continuity equation. The boundary conditions for particles are absorbing; particles reaching the boundaries of the simulation box are frozen there. For the solution of Maxwell’s equations, damping layers are employed near the simulation box boundaries in order to eliminate spurious reflection of outgoing electromagnetic waves, as described in [31].

Two kinds of targets and laser pulse parameters are used in our PIC simulations. In the first part of this paper (section 3), the target consists of 0.2 µm thick foil, with or without a periodic structure attached to the front, laser-irradiated, surface (see figure 1). The shape of the structure is spherical, rectangular or triangular. The latter two shapes are more complicated for optimization as they offer an additional degree of freedom (sphere—diameter; rectangle—width and depth; triangle—height and opening angle). Moreover, it is observed that the shape of the surface structure does not have a significant effect on laser pulse absorption. Therefore, we have chosen to use a spherical shape in the reminder of this paper due to its simplicity. It is worth noting that targets with a surface layer of microspheres can be prepared relatively easily, as will be discussed in the first part of section 4. In this section, the foil thickness is increased to 0.5 µm, as such a thickness may better correspond to the optimum one for obtaining the maximum energy of the accelerated proton if the short laser pulse has a non-negligible prepulse. Moreover, a thicker foil can better support the surface structure without being damaged or bent.

All of the targets used in this paper consist of two species of ions (a homogeneous 1:2 mixture of C^4+ and protons) and free electrons with the initial density of 40× critical density. The density profile on the target surface is step-like with the exception of section 4, where the influence of the density ramp is discussed. The targets are placed in a simulation box of size 17λ in the transverse direction. The incident laser pulse always propagates in the same direction (from the bottom) but the target may be rotated by the laser incidence angle. The simulation box size in the longitudinal direction thus depends on the incidence angle and ranges between approximately 21 and 35λ. The initial electron and ion temperatures are set to 50 eV, unless otherwise stated. This low temperature is used to ensure that the target does not significantly expand by itself on the simulation time scale. The characteristic velocity of target expansion, the ion acoustic velocity, multiplied by our typical simulation time (0.2 ps) gives the target expansion of about 10 nm, which is well below our typical target dimensions.

The targets are irradiated by p-polarized laser pulses with a wavelength of 800 nm and the temporal profile sin^2(πτ/τ), where τ is the laser pulse duration. A 20 fs long (full width at half maximum (FWHM)) laser pulse with a maximum intensity of 1.8 × 10^19 W cm^-2 is used in section 3, whereas in section 4 the pulse duration is increased to 40 fs and the maximum intensity is decreased to 9 × 10^18 W cm^-2. The laser incidence is in the normal direction with respect to the target surface in section 3. Instead of normal incidence, we use a rather low incidence angle of 10° or the standard incidence angle of 45° in section 4. The transverse intensity profile of the laser pulse in our simulations is Gaussian with the FWHM of 4.7λ, and the laser pulse is always
Figure 1. The targets used in our 2D PIC simulations to study the influence of the shape of the surface structure on laser pulse absorption. The initial free-electron density in the target is plotted in units of critical density. Only a small square section of the target is plotted. The laser pulse (with wavelength $\lambda$) is incident from the bottom.

Table 1. Comparison of the results of PIC simulations with the targets plotted in figure 1. The parameters of hot electrons are measured after the end of the laser target interaction. The electron divergence is the average angle of electrons with kinetic energy higher than the rest mass energy ($m_e(c)^2$) with respect to the target normal.

| Target (figure 1) | Electron temperature (MeV) | Electron divergence (°) | Laser absorption (%) |
|-------------------|-----------------------------|-------------------------|----------------------|
| (a)               | 0.10                        | 14.8                    | 3.8                  |
| (b)               | 0.40                        | 39.7                    | 55.2                 |
| (c)               | 0.42                        | 41.8                    | 80.5                 |
| (d)               | 0.37                        | 40.9                    | 43.9                 |

launched at time 0 from the front side of the simulation box, which corresponds to the bottom side of figures containing ion density snapshots.

3. Laser absorption: dependence on the shape and the size of the surface structure

The results of PIC simulations concerning the absorption of laser pulses and the acceleration of hot electrons in the interaction with the targets plotted in figure 1 are summarized in table 1. These results indicate that surface structures with sizes of the order of the laser wavelength may boost laser energy absorption significantly. The energy is absorbed in particular by hot electrons. In the case of a flat foil surface, the temperature and the number of hot electrons are much lower; on the other hand, these electrons form a collimated beam. The structure on the target surface causes much higher absorption but the hot electron beam is very divergent. This behavior seems to be quite general, as it has been observed in all of our simulations with short (sub-100 fs) and intense ($I \gtrsim 10^{18}$ W cm$^{-2}$) laser pulses. This conclusion should apply neither to long laser pulses (> 1 ps), because the surface structure may expand during the interaction, nor to the ultra-relativistic regime ($I \gtrsim 10^{21}$ W cm$^{-2}$), where radiation pressure becomes extremely high and the energy absorption is dominated by different processes [32].

The enhancement of absorption of a short intense laser pulse due to the presence of a micro- or a nano-structure on the target surface has been ascribed to different processes in recent publications, e.g. surface plasmon resonance excitation [18, 33, 34] and multipass stochastic...
Figure 2. Energy distributions of electrons in the targets from figure 1 at the end of the laser target interaction (panel (a)). The angular distribution of electrons at the end of the laser target interaction for the case of a flat foil surface (panel (b)) and for the case of a structured foil surface (target c in figure 1, panel (c)). The angle is defined with respect to the laser incidence direction.

heating [35]. For a sphere with a diameter close to the laser wavelength, numerical solutions of Mie scattering theory demonstrate that the field at the surface of the sphere can be significantly higher than the field of the incident laser wave [36]. This enhancement of the field may be considered also as a source of increased absorption [17, 36]. However, such a field enhancement is not observed in our PIC simulations with bulk targets, which are discussed at the end of the next section. In simulations with thin foils, we observe that the maximum electric field is increased by about 50% for the same parameters. As there is no other difference than the target thickness, it is clear that the electric field enhancement in our simulations with thin foils is due to hot electron recirculation, because the main difference between thin and bulk targets lies in the efficiency of the recirculation process.

A number of different effects may contribute to higher absorption using structured targets. As structured targets have a significantly larger surface area, more particles can interact with the laser field. Moreover, as the angle of incidence of the laser pulse is not normal, vacuum heating [37] and resonance absorption [38] can take place. Last but not least, the structure is screening the incident laser wave but the accelerated electrons can propagate through it and consequently they can more easily get out of phase with the laser wave and thus gain its energy more efficiently. One can thus imagine a similar absorption process as the multipass stochastic heating in the case of clusters [35]. The enhanced dephasing of electrons due to the presence of surface structure may also be the source of the broader angular distribution of hot electrons, which is observed in our simulations.

The electron energy distributions and the angular distributions of electrons are plotted in figure 2. The plotted data essentially confirm the results presented in table 1. Namely, the number of hot electrons strongly increases if the target has a structured surface, but the angular distribution of hot electrons changes from a relatively narrow beam, which is typical of flat foil targets, into an almost isotropic one, which corresponds to laser interaction with clusters [39].

Electron energy distributions plotted in figure 2 represent all of the electrons in the simulation box, approximately at the time when the maximum laser intensity reaches the target. These distributions can be considered as distributions of the source of hot electrons in the case of short laser pulses, because according to our PIC simulations they are almost identical to the distributions of hot electrons propagating into bulk targets.
Figure 3. Laser energy absorption versus the diameter of microspheres on the
target surface (panel (a)). Part of the target with a surface layer composed of
microspheres with random diameter (panel (b)). The color bar gives the color
scale for the electron density in units of critical density.

In figure 3(a), the dependence of laser energy absorption on the size of the surface structure
is plotted for targets covered by spheres. The spheres in our simulations are always closely
packed and thus there is just one parameter characterizing the structure—the sphere diameter.
It results from figure 3(a) that the optimum size of spheres for obtaining absorption higher
than 50% is close to the laser wavelength. The targets with rectangular and triangular surface
structures have more degrees of freedom (at least width and height) and the dependence would
be more complex, e.g. [23]. Recent PIC simulations [20] also indicate that it is possible to
achieve almost complete absorption if the structure is tiny and sufficiently long in the laser
propagation direction.

Until now, we have considered only targets with regular, grating-like structure on the
surface. From the point of view of target fabrication, it is interesting to know whether this
regularity is necessary or whether the structure can be irregular to some degree. To answer
this question, we have performed a simulation placing an irregular surface structure on the
target (figure 3(b)). The spheres on the surface have random diameter, which is in the range
of 0.25–1λ, and they are closely packed. The other simulation parameters remain unchanged.
The laser energy absorption of 57% we found in our simulation is even higher than the
maximum absorption obtained in simulations with regular structure. One cannot draw a general
conclusion from only one simulation with random parameters; nevertheless, this result indicates
that absolute regularity of the structure is not necessary to obtain relatively high absorption.

3.1. Ion acceleration scaling with the size of the surface structure

In the previous section, we have shown that the structure on the target surface can significantly
increase laser energy absorption and raise the temperature and the number of hot electrons. The
aim of this section is to show whether and how efficiently the kinetic energy of hot electrons
is transferred into fast ions in the sheath field at the target surface (TNSA). For the sake of
simplicity, we concentrate again on targets with a spherical surface structure. Two important
parameters describing accelerated ions and their dependence on the sphere size and the laser
incidence angle are studied. In particular, we concentrate on the maximum ion energy and
the total energy of accelerated ions normalized to the laser pulse energy (i.e. transformation
efficiency of energy into fast ions).
Figure 4. The maximum proton energy and the energy transformation efficiency from the laser pulse into all ions in simulations with microspheres on the target surface (panel (a)). The results correspond to the time of about 0.2 ps after the laser target interaction. In panel (b), there are two functions of hot electron temperature $T$, hot electron density $n$ and the target thickness $d$, which includes the layer of spheres. These functions determine the maximum energy and the efficiency in panel (a). The electron temperatures and densities include all hot electrons in the simulation box after the laser–target interaction.

The maximum energy of accelerated protons and the energy transformation efficiency from the laser pulse into all ions are plotted in figure 4(a). The results are taken about 0.2 ps after the laser–target interaction. This time interval is long enough to enable the most important part of the ion acceleration process to be accomplished. Nevertheless, the transfer of energy from electrons to ions is still not over and thus one should read the results as qualitative features and not as exact numbers.

The dependence of maximum proton energy on the size of microspheres in figure 4(a) is quite similar to the dependence of laser energy absorption in figure 3(a). According to the analytical model [40] and the arguments of [41], the maximum energy of ions depends linearly on the hot electron temperature, whereas the dependence on the density of hot electrons is only logarithmic, i.e. $E_{\text{max}} \sim T \times \ln^2(n)$. However, this theory does not take into account the effect of target thickness. If the target thickness $d$ is smaller than the spatial length of the laser pulse (laser pulse duration times the velocity of light), hot electron recirculation may become important. This recirculation process manifests itself mainly with increasing the concentration of hot electrons, whose number scales approximately linearly with decreasing the target thickness. The recirculation of hot electrons is important also in our simulations and thus the dependence on hot electron density $n$ should be replaced by the dependence on $n/d$. The function $T \times \ln^2(n/d)$ is plotted in figure 4(b) and its dependence on the sphere size is very similar to that of the maximum proton energy.

The energy transformation efficiency plotted in figure 4(a) attains its maximum at smaller sphere size than the maximum proton energy. The efficiency depends in particular on the product $T \times n$ [41], and as the density of hot electrons scales again with the target thickness, the dependence on target thickness is now much stronger. This reasoning is confirmed by
Figure 5. (a) Scanning electron microscope (SEM) image of the target surface covered by a monolayer of polystyrene spheres with a diameter of about 0.9 µm. (b) SEM image of a thin mylar foil (100 nm) covered by polystyrene spheres (0.26 µm). Image is taken at the border of the foil, where the spheres are not regularly arranged due to the cutting process. (c) Atomic force microscope image of the surface of a common commercially available (supplied by Goodfellow SARL) thin aluminum foil (2 µm thick).

Comparing the efficiency in figure 4(a) with the function $T \times n/d$ in figure 4(b). Thus, it is possible to say that the advantage of small-size targets, where hot electrons efficiently recirculate, is more important for transformation efficiency than for the maximum ion energy, as recently experimentally confirmed [8]. It is also worth noting that increasing the depth of the surface structure may lead to higher absorption efficiency, but not always to a higher energy of accelerated ions.

4. Ion acceleration in targets covered by a monolayer of polystyrene microspheres

In the previous section, it has been demonstrated that a monolayer of microspheres deposited on the surface of the target may be suitable for increasing the laser energy absorption and electron and ion acceleration efficiency. The sphere size being similar to the laser wavelength has been identified as most suitable in this respect. A target covered by a layer of microspheres is not only relatively simple for theoretical and simulation studies but also suitable for initial experimental studies. Polystyrene microspheres with different diameters in the range of 100–1000 nm are commercially accessible and their deposition on the target surface is quite straightforward.

The method of deposition of the monolayer on the targets’ surface is described below in a simplified way. A water dispersion of polystyrene microspheres is mixed with ethanol (usually 1 : 1) and carefully applied on the surface of water in a Petri dish using a glass pipette with a bent tip [42]. Self-assembly at the interface of water/air results in the creation of a compact monolayer of close-packed microspheres. The target is submerged under the monolayer and then lifted up slowly so that the monolayer remains on its upper side. The result is a piecewise homogeneous monolayer of closely packed microspheres attached to the target surface, which can be seen in figures 5(a) and (b).

At this point, we have to add a short note concerning the possible future experimental investigation of targets with a micro-structure on the surface. We have inspected the surface of commercially accessible 2 µm thick aluminum foil using atomic force microscopy. The result is plotted in figure 5(c). It can be seen that the foil surface looks like an irregular grating with...
variable sized grooves probably due to the fabrication process. As the groove size is comparable to the wavelength of Ti:sapphire laser, which is most commonly used in ion acceleration experiments, it is clear that this grating can significantly influence the results of experiment. Therefore, one has to either polish the target surface using some chemical or mechanical method or contrast the target with optical quality surface requirements.

Let us return to the simulation results. In this section, we restrict ourselves only to the diameters of microspheres in the surface layer of 0.5 or 1\(\lambda\), where \(\lambda\) is the laser wavelength, as, according to the discussion in the previous section, these sizes are most appropriate for efficient ion acceleration. The laser pulse incidence angle is either 45\(^\circ\) or 10\(^\circ\) with respect to the target surface normal direction. The angle of 10\(^\circ\) is used instead of normal incidence because it is closer to the experimental practice aiming to avoid strong laser pulse back-reflection. An overview of targets and angles of incidence used in this section is presented in table 2.

The results of these simulations concerning laser energy absorption and electron acceleration are presented in figure 6. In panel (a), the laser energy absorption reaches almost 60% when the microspheres are present, and it does not strongly depend on the incidence angle or sphere size in the range considered here. The energy absorption of 60% is also in accordance with the absorption observed in the previous section in figure 3(a). Moreover, for smaller sphere size and almost normal incidence, the absorption drops to about 40%, which is also consistent with figure 3. For raw flat foils, the laser energy absorption is less than 20%, but significantly higher than the absorption for the normal incidence. This is due to the nonzero incidence angle. One can see that a weak change in the incidence angle may have a significant effect on laser energy absorption. The case of normal incidence onto an absolutely flat target is extremely inefficient and perhaps not fully realistic.

The energy distributions of electrons accelerated into the target are plotted in figure 6(b). These distributions are recorded in simulations with thin foil targets and they include all

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**Table 2.** Overview of the target and simulation parameters used in this section.

| Target | A | B | C | D | E | F |
|--------|---|---|---|---|---|---|
| Sphere diameter (\(\lambda\)) | 0 | 0.5 | 1 | 0 | 0.5 | 1 |
| Incidence angle | 10\(^\circ\) | 10\(^\circ\) | 10\(^\circ\) | 45\(^\circ\) | 45\(^\circ\) | 45\(^\circ\) |

**Figure 6.** (a) Laser energy absorption in the targets specified in table 2. (b) Energy distributions of electrons accelerated in simulations with targets from table 2 recorded at the end of the interaction.
The energy–angular distributions of hot electrons accelerated in simulations with target configurations from Table 2: configuration A, panel (a); B, panel (b); C, panel (c); and D, panel (d). The angle $\alpha$ is measured with respect to the target surface normal direction.

electrons in the entire simulation box at the end of the laser target interaction. Comparing these distributions with the ones calculated for bulk target (with the same parameters), where the electrons crossing an absorbing boundary in the target are recorded and substituted by thermal ones, it is found that the distributions are almost identical. This is not surprising for the very short laser pulse durations, as hot electrons do not have enough time to transfer a significant amount of energy to ions in a thin foil on the time scale of half the laser pulse duration (we assume that most of the hot electrons are generated at the time of peak laser intensity on the target). Therefore, one can consider the distribution of hot electrons calculated for a thin foil also as a source of hot electrons propagating into the bulk target.

In figure 6(b), it can be seen that the distributions for the target configurations C, E and F are quite similar, which is consistent with a similar laser energy absorption observed in figure 6(a). The hot electron temperature is about 500 keV in these three cases. The other two cases A and D, where the laser energy absorption is quite inefficient, correspond to the targets where the surface layer of microspheres is absent. These distributions have temperatures of about 190 and 310 keV. The increase in hot electron temperature in comparison with results for normal incidence presented in Table 1 (target a) indicates that there are some additional absorption mechanisms in the case of oblique incidence, which are responsible for the production of more energetic electrons. As the density profile on the target surface is very steep, we can rule out resonance absorption and ascribe the hot electron production to vacuum heating.

As already discussed in the previous section, the angular distribution of hot electrons accelerated in the laser interaction with a structured target surface is almost isotropic. This can also be seen in figure 7, where the energy–angular distributions of electrons recorded in our simulations are presented. The cases in panels (a) and (d) correspond to flat target surfaces irradiated at $10^\circ$ and $45^\circ$, respectively. The angle $\alpha$ is measured with respect to the target surface normal direction. It can be seen that for the flat target surface, hot electrons propagate in a collimated beam. The other two cases (panels (b) and (c)) both correspond to the incidence angle of $10^\circ$ but for different sizes of microspheres at the surface. The angular distribution of hot electrons is rather wide and the source of hot electrons is nearly isotropic, like in the previous section. The dependence on the size of the microspheres is not observed in the range of sphere sizes used here. Similar distributions are also found for the $45^\circ$ incidence angle and thus these distributions are omitted here.

The efficiency of conversion of laser energy into fast protons accelerated in the TNSA process from both surfaces of the thin foil ($0.5 \mu m$ thickness excluding the microspheres) is
Figure 8. (a) The efficiency of conversion of laser energy into fast protons with energy higher than 1 MeV accelerated outside from the front and rear sides of the target. The energy distributions of fast protons accelerated by the TNSA process at the target front (b) and rear (c) sides. The target configurations A, B, etc correspond to the parameters specified in table 2.

plotted in figure 8(a). This efficiency includes only protons accelerated to energies higher than 1 MeV and it is measured 0.2 ps after the laser target interaction. As we do not include carbon ions and lower-energy protons, there is a large difference between this conversion efficiency and the one presented in figure 4(a). One may therefore arrive at the conclusion that only about one quarter of the total energy of ions is contained in fast protons. Otherwise, the conversion efficiency shows similar trends to the laser pulse absorption presented in figure 6(a).

In figures 8(b) and (c), the energy distributions of fast protons accelerated from the front and rear sides of the targets are presented. In general, one can say that all of the distributions are exponential with a high energy cut-off. The slopes of exponential distributions for the targets with microspheres are similar to each other; only the numbers of accelerated protons and the cut-off energy differ. The highest cut-off energy is obtained from both the target sides for the incidence angle of 10° and the sphere size of \( \lambda \). This is consistent with the highest absorption (figure 6(a)) and conversion (figure 8(a)) efficiencies. However, the difference between the cut-off energies at the front and rear sides is not very significant for the targets with microspheres. At this point, we have to note that we have not observed any significant difference in angular distribution of protons accelerated from the targets with and without the structure on the surface. Therefore, we do not discuss the angular distribution here.

The distributions of protons accelerated from flat foils contain far fewer particles and they have much lower cut off energy. The extreme case is the distribution of protons accelerated from the target front side for the target configuration A (table 2). Here, one can see that the distribution of protons accelerated from the front side differs very significantly from the distribution of protons accelerated from the rear side, which is not the case in any other simulation. This difference can be better understood from the proton density snapshots presented in figure 9.

The initial density of protons in the target (in panel (a)) is homogeneous. In panel (b), the density snapshot taken 0.1 ps after the laser target interaction shows a bow-like shock propagating into the foil. These are the ions accelerated into the target by the radiation pressure of the laser pulse. The protons contained in this shock are of lower energy (less than 1 MeV) and
Figure 9. The density of protons in the target without the surface layer of microspheres irradiated at a 10° angle of incidence at the beginning (a) and 0.1 ps after the end of the laser target interaction (b). The laser pulse is incident from the bottom, and the density of protons in units of the critical density is represented by colors.

thus they are not interesting in the context of this paper. However, the shock accelerated into the target reduces the efficiency of proton acceleration in the TNSA process from the target front side. This shock is particularly strong in the case of near-normal incidence and a flat foil surface, when the TNSA process is suppressed due to low laser energy absorption into hot electrons.

4.1. Influence of the density gradient

Even very-low-intensity laser prepulses may induce some evaporation from the target surface and the vapor may be ionized by the rising edge of the main laser pulse [43]. Therefore, it is important to include a short steep plasma density profile on the target surface and to study its influence. The density profile can be included easily if the target surface is flat. However, the expansion of the structure is not planar (1D) and thus it is more complicated to describe the expanding plasma. To make the shape and the scale of the preplasma realistic also for the structured target surface, we have used the following procedure. The interaction with the main laser pulse is delayed by about 150 fs. The target is initialized as in the simulation without preplasma, but the temperatures of electrons and ions are both set to 1 keV. The plasma is allowed to expand from the front side of the target for about 100 fs (a reflecting boundary condition at the rear side precludes expansion during this period) and after that the particle energies are resampled from the Maxwellian distribution with the same temperature, as in previous simulations (i.e. 50 eV). This approach enables us to obtain a realistic density profile during a reasonably short computational time. Moreover, we start the interaction with the same temperatures of electrons and ions and thus we can observe the effect of the density profile in addition to other effects. The density profile on the target rear surface is not included.

The density profiles of targets with preplasma on the surface, which are studied in our simulations, are plotted in figure 10. The target in panel (a) is a simple flat foil with an exponential density profile on the front surface. The scale length \( L \) of the density profile is 0.04\( \lambda \). An exponential density profile with a similar scale length is produced on the surface of the structured target using the approach described above. This target can be seen in panel (b). Apart from the density profiles on the front side, both of these targets correspond to configurations A and C described in table 2.
Figure 10. (a) The ion charge density (normalized on charge at critical density) profile at the beginning of the laser interaction with the flat target (target A), which has an exponential density ramp at the front, laser-irradiated side. (b) The same density profile for the target with microspheres on the surface (target C), which has significantly expanded prior to the interaction with the laser pulse. The laser pulse is incident from the bottom.

As one may expect, laser energy absorption in the case of a flat target surface increases with plasma density scale length (in the range of our interest, $L \ll \lambda$). For $L = 0.04\lambda$, the relative absorption increases from 11 to about 13% (18% relative increase). An opposite trend is observed for the target with the surface structure, where the density profile smoothes the sharp borders of the structure and thus weakens its effect. In this case, the absorption decreases from 59% to about 54% (7% relative decrease).

The energy distributions of protons accelerated from target rear sides are compared in figure 11(a). The effect of the density profile on ion acceleration is clearly significant only in the case of target A (from table 2). For this target, the maximum energies of accelerated protons and the conversion efficiency into fast protons with energy higher than 0.1 MeV have both increased by about 50%. This is not surprising as the temperature of fast electrons in the target with the density profile is significantly higher (250 keV) in comparison with the target without the profile (190 keV). In consequence, the large difference in the energy distribution of fast protons is caused by fast electrons, which are accelerated more efficiently at the surface of the flat target with the density profile. This result indicates the importance of the laser pulse contrast for experiments with targets having a micro-structure on the irradiated surfaces. If the contrast is not sufficient, the effect of surface structure may not be detected. In this respect, we would like to note that most previous experiments with micro-structure on the target surface have been performed with moderate laser intensity of the order of $10^{16}$ W cm$^{-2}$ and thus the demands on the contrast were not so stringent.

4.2. Acceleration from the front side of a bulk target

Acceleration of ions from the front side of a bulk target into vacuum is not very interesting from the application point of view. The reason is that the efficiency of such an acceleration process is not so high as it takes place only during the laser–target interaction and cannot benefit from electron recirculation. When the laser field is over, there is no force to pull electrons from the
Figure 11. The energy distribution of protons accelerated from the rear side of targets A and C (from table 2) and the targets with density profiles plotted in figure 10. The distributions are compared 0.2 ps after the laser target interaction. (b) The energy distributions of protons accelerated out of the target from its front side. The distributions for thin and bulk targets are compared 130 fs after the laser target interaction.

target into vacuum, the electrons are dragged back into the target by a quasi-static electric field and their energy is absorbed in the target interior. After that, ion acceleration can be driven only by thermal expansion and such a process is not efficient in the case of short, femtosecond laser pulses.

Nevertheless, bulk targets may be relevant to proof of principle experiments studying the influence of surface micro-structure. As already mentioned, the targets with a structured surface should be compared with targets with a highly flat surface (e.g. of optical quality). It might be difficult to prepare a foil target, which is very flat and very thin at once. However, polishing surfaces of bulk targets is not so difficult and thus a very flat bulk target may serve as an intermediate step to experimentally demonstrate the effect of the target surface on ion acceleration driven by laser–target interaction.

In our simulations, bulk targets are realized by using an absorbing boundary condition at the rear side of the target. The particles reaching this boundary are absorbed and reemitted with the initial thermal distribution. The results calculated for bulk targets A and C (according to table 2) are compared in figure 11(b) with the results obtained for thin foils. The maximum energy and the efficiency of ion acceleration are significantly reduced in bulk targets, but the large difference between the results for targets with and without surface structure still exists.

5. Conclusions

Target normal sheath acceleration of ions from thin foil targets with a flat or structured front surface is studied in this paper using 2D PIC simulations. The structure on the front surface may significantly boost the energy absorption of intense laser pulses with ultra-high contrast and increase the hot electron temperature and density. This leads to higher ion acceleration efficiency and maximum ion energy in the case of thin foil targets, which may benefit from hot electron recirculation. The angular distribution of hot electrons accelerated in the interaction of the laser pulse with a structured surface is very wide. However, the angular distribution of accelerated ions is not significantly affected and the ions form a narrow beam.
The laser absorption process depends on the shape and size of the structure on the surface. The maximum laser pulse absorption is obtained when the characteristic size of the surface structure is comparable to the laser wavelength. The high energy cut-off of the ion energy distribution and the ion acceleration efficiency depend not only on laser energy absorption but also on efficient hot electron recirculation. Therefore, they reach their maximum value when the absorption is efficient but the layer on the target surface containing the structure is as thin as possible. These two conditions result in an optimum size of the structure. For a monolayer of closely packed microspheres on the target surface, this optimum is found in the range of 0.5–1\(\lambda\), where \(\lambda\) is the laser wavelength. We propose to use a target with a monolayer of closely packed polystyrene microspheres in experiments and provide a short description of the target preparation process.

The influence of the angle of laser pulse incidence is studied in section 4. It is found that for targets with microspheres, there is a weak dependence of the results on the incidence angle, which is not the case for flat foil targets. For the target thickness used in our simulation, it is found that accelerations from both of the target surfaces are similar with the exception of the flat foil irradiated at a small incidence angle. In this case, absorption is inefficient and the laser radiation pressure launches a strong shock wave into the target, which suppresses ion acceleration efficiency from the front side.

The density profile on the target surface, which may be induced by a weak laser prepulse, is included at the target front side and its influence on ion acceleration is studied. The density profile weakens the effect of the surface structure, while it provides conditions for more efficient laser absorption by flat foils. If the scale length of the density profile becomes comparable to the size of the surface structure, the effect of the structure may disappear completely.

In the proof of principle experiments studying the influence of the surface structure on ion acceleration, it might be possible to study ion acceleration in the backward direction from the front side of a bulk target. The surface of a bulk target can be polished more easily and thus it could be possible to compare the influence of the structure with a really flat target surface. Moreover, the effect of the surface structure on ion acceleration in the bulk target should be sufficiently strong, as demonstrated in the last part of this paper.

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References

[1] Wilks S C et al 2001 Phys. Plasmas 8 542–9
[2] Hatchett S P et al 2000 Phys. Plasmas 7 2076
[3] Snively R A et al 2000 Phys. Rev. Lett. 85 2945–8
[4] Cowan T et al 2004 Phys. Rev. Lett. 92 204801

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[5] Borghesi M et al 2004 Phys. Rev. Lett. 92 055003
[6] Borghesi M et al 2007 J. Phys.: Conf. Ser. 58 74–80
[7] Ceccotti T et al 2007 Phys. Rev. Lett. 99 185002
[8] Buffeuchoux S et al 2010 Phys. Rev. Lett. 105 015005
[9] Batani D et al 2010 New J. Phys. 12 045018
[10] Kaluza M et al 2004 Phys. Rev. Lett. 93 045003
[11] Levy A et al 2007 Opt. Lett. 32 310–2
[12] Hu G Y et al 2010 Phys. Plasmas 17 083102
[13] Khattak F Y et al 2005 Europhys. Lett. 72 242–8
[14] Kulcsar G et al 2000 Phys. Rev. Lett. 84 5149–52
[15] Murnane M M et al 1993 Appl. Phys. Lett. 62 1068–70
[16] Nishikawa T et al 2004 J. Appl. Phys. 96 7537–43
[17] Palchan T et al 2007 Appl. Phys. Lett. 90 041501
[18] Rajeev P et al 2003 Phys. Rev. Lett. 90 115002
[19] Sumeruk H A et al 2007 Phys. Rev. Lett. 98 045001
[20] Cao L et al 2010 Phys. Plasmas 17 043103
[21] Mikhailova Y M et al 2005 Quantum Electron. 35 38–42
[22] Raynaud M et al 2007 Phys. Plasmas 14 092702
[23] Wang W M et al 2008 Phys. Plasmas 15 030702
[24] Takahashi K et al 2010 Phys. Plasmas 17 093102
[25] Bagchi S et al 2008 Laser Part. Beams 26 259–64
[26] Bagchi S et al 2007 Appl. Phys. Lett. 90 141502
[27] Gibbon P and Rosmej O N 2007 Plasma Phys. Control. Fusion 49 1873–83
[28] Nodera Y et al 2008 Phys. Rev. E 78 046401
[29] Psikal J et al 2006 Czech. J. Phys. 56 B515–B521
[30] Umeda T et al 2003 Comput. Phys. Commun. 156 73–85
[31] Umeda T 2001 Comput. Phys. Commun. 137 286–99
[32] Ping Y et al 2008 Phys. Rev. Lett. 100 085004
[33] Boyd G T et al 1984 Phys. Rev. B 30 519–26
[34] Hu G Y et al 2010 Phys. Plasmas 17 083102
[35] Breizman B N et al 2005 Phys. Plasmas 12 056706
[36] Sumeruk H A et al 2007 Phys. Plasmas 14 062704
[37] Brunel F 1987 Phys. Rev. Lett. 59 52–5
[38] Krueer W L 1988 The Physics of Laser Plasma Interactions (Reading, MA: Addison-Wesley)
[39] Shao Y L et al 1996 Phys. Rev. Lett. 77 3343–6
[40] Mora P 2003 Phys. Rev. Lett. 90 185002
[41] Psikal J et al 2010 Phys. Plasmas 17 013102
[42] Kosiorek A et al 2004 Nano Lett. 4 1359–63
[43] Wharton K et al 2001 Phys. Rev. E 64 025401