Proton acceleration by moderately relativistic laser pulses interacting with solid density targets

To cite this article: Erik Lefebvre et al 2010 New J. Phys. 12 045017

View the article online for updates and enhancements.

Related content
- Review of laser-driven ion sources and their applications
  Hiroyuki Daido, Mamiko Nishiuchi and Alexander S Pirozhkov
- Carbon ion acceleration from thin foil targets irradiated by ultrahigh-contrast, ultraintense laser pulses
  D C Carroll, O Tresca, R Prasad et al.
- Short pulse laser interaction with micro-structured targets: simulations of laser absorption and ion acceleration
  O Klimo, J Psikal, J Limpouch et al.

Recent citations
- Large-scale studies of ion acceleration in laser-generated plasma at intensities from 10^{10} W/cm^{2} to 10^{19} W/cm^{2}
  L. Torrisi
- Investigation of ionization speed in field ionization with laser–plasma interaction
  Y. Tian et al
- Water radiolysis with heavy-ion beams at GANIL. Back to 20 years of investigations
  G Baldacchino
Proton acceleration by moderately relativistic laser pulses interacting with solid density targets

Erik Lefebvre\textsuperscript{1,7}, Laurent Gremillet\textsuperscript{1}, Anna Lévy\textsuperscript{2}, Rachel Nuter\textsuperscript{1}, Patrizio Antici\textsuperscript{3}, Michaël Carrière\textsuperscript{1}, Tiberio Ceccotti\textsuperscript{4}, Mathieu Drouin\textsuperscript{1}, Julien Fuchs\textsuperscript{2}, Victor Malka\textsuperscript{5} and David Neely\textsuperscript{6}

\textsuperscript{1} CEA, DAM, DIF, 91297 Arpajon, France
\textsuperscript{2} Laboratoire pour l’Utilisation des Lasers Intenses, UMR 7605 CNRS/CEA/Ecole Polytechnique/Paris VI, 91128 Palaiseau, France
\textsuperscript{3} Istituto Nazionale di Fisica Nucleare, Via E Fermi, 40, 00044 Frascati, Italy
\textsuperscript{4} Service des Photons, Atomes et Molécules, CEA/DSM/IRAMIS, CEN Saclay, 91191 Gif-sur-Yvette, France
\textsuperscript{5} Laboratoire d’Optique Appliquée, UMR 7639 ENSTA/CNRS/Ecole Polytechnique, 91761 Palaiseau, France
\textsuperscript{6} Central Laser Facility, Rutherford Appleton Laboratory, Chilton, Didcot, Oxon OX11 0QX, UK
E-mail: erik.lefebvre@cea.fr

Received 9 January 2010
Published 30 April 2010
Online at \url{http://www.njp.org/}
doi:10.1088/1367-2630/12/4/045017

Abstract. We use two-dimensional (2D) particle-in-cell simulations to study the interaction of short-duration, moderately relativistic laser pulses with sub-micrometric dense hydrogen plasma slabs. Particular attention is devoted to proton acceleration by the target normal sheath mechanism. We observed that improved acceleration due to relativistic transparency of the target is unlikely for the shortest pulses, even for ultra-thin ($\sim$10 nm) targets. This mechanism would require either longer pulses or higher laser intensities. As the target density and thickness, pulse length, duration and polarization are varied, we see clear relationships between laser irradiance, hot electron temperature and peak proton energy. All these explain why, at a given incident laser energy level, the highest proton energy is not always obtained for the shortest-duration, highest-intensity pulse.

\textsuperscript{7} Author to whom any correspondence should be addressed.
1. Introduction

Particle acceleration to MeV energies with short-duration, high-intensity laser pulses is made possible by strong electromagnetic fields that can be excited during the interaction of these light pulses with matter. Upon interaction with a thin solid target, a large fraction of laser energy can be converted to a beam of relativistic electrons. These electrons rapidly form a hot plasma cloud around the target, setting up a large-amplitude, quasi-static electrostatic field at its front and rear surfaces. This field leads to acceleration of positive ions off these surfaces, and protons originating from hydrogenated pollutants deposited on the target are most easily accelerated. Many experimentally observed ion beams [1]–[7] have been attributed to this mechanism, known as target normal sheath acceleration (TNSA) [8]. Owing to their characteristics (laminarity, short duration, point-like source, etc) [9], these beams are interesting candidates for applications such as isochoric heating of matter [10, 11], probing of quasi-static electrostatic fields [12] or radiography of rapidly imploding, solid density matter [13]. Progress towards routine and efficient realization of these applications requires good knowledge of proton acceleration physics and how source characteristics are affected by laser and target parameters. In this respect, experiments and numerical simulations can provide complementary findings. Modelling, for instance, can suggest directions towards optimized proton sources before they can be explored in experiments [14, 15].

Recent numerical studies of laser ion acceleration [2, 8, 14] have focused on high-intensity pulses, in the $10^{20}$ W cm$^{-2}$ range, interacting with moderately overdense targets, between 10 and $40n_c$. Some of these simulations exhibit an optimal acceleration regime, corresponding to very-high-intensity pulses and very thin targets, which can be transparent to the laser pulse by virtue of relativistic self-induced transparency [16], or due to the ultra-fast target density decrease resulting from its expansion [17]. Volumic heating of the plasma electrons can occur in this case, so that the hot electron density driving ion acceleration is close to the plasma density [14, 18]. This contrasts with the opaque target regime, in which the hot electron density is typically limited to the critical density or is much lower than this density due to the lateral spread of the hot electrons during their transport through the target [4, 5]. As the amplitude of the electrostatic field driving ion acceleration is directly related to the hot electron temperature and density [19, 20], acceleration to higher energy is obtained in the relativistically transparent regime [14].

Experimental confirmation of this behaviour has been the subject of some efforts since then [6, 7, 18, 21]. Using numerical simulations to explore the variation of the ‘transparent’ acceleration regime with pulse intensity, target thickness and density, we concluded [14]...
that the optimum target thickness would scale linearly with intensity and inversely with target density. Scaling our simulation results to experimentally relevant conditions, one would expect the ‘transparent regime’ proton acceleration to take place for target thicknesses of the order of 1–3 nm for a laser pulse with 30 fs duration, 0.8 µm wavelength and 10^{19} \, W \, cm^{-2} \, irradianace. The major difficulty in any attempt to observe this effect experimentally stems from amplified spontaneous emission (ASE) and other light prepulses that may leak from the laser chain, be absorbed by the target and perturb the rear surface prior to interaction with the main, high-intensity pulse. Typical prepulse levels, with contrast ratios of 10^{-6} to 10^{-7}, generate perturbations moving through the target at speeds of several \mu m \, ns^{-1} [4, 6, 22], and nanometre-scale targets would therefore require sub-picosecond prepulses to be immune to ASE perturbation. Plasma mirrors, single- or double-staged, have proven to be an efficient means for prepulse reduction by two to four orders of magnitude [23, 24]. For a 10^{19} \, W \, cm^{-2} \, main pulse, the prepulse level is then brought down below 10^{10} \, W \, cm^{-2}, safely below the plasma formation threshold. We may therefore assume that the main pulse interacts with an unperturbed target, having sharp density gradients on both surfaces, high density and small thickness. As laser light is less efficiently coupled to very overdense targets at normal incidence, and as laser energy and irradiance are somewhat reduced by the plasma mirror, these experiments are usually conducted with oblique incidence of the pulse on the target, typically at 45°, in \, p-polarization, so as to maximize absorption.

As a result of this context, and motivated by the first experimental attempts fielding very overdense, ultra-thin targets [6, 7, 18, 21], we set out to explore ion acceleration in this range of parameters with numerical simulations. The goal of the present paper is therefore to model and study the interaction of moderately relativistic laser pulses (intensity between 10^{18} and 2 \times 10^{19} \, W \, cm^{-2}) with very overdense \, (n_e > 100 n_c), ultra-thin (thickness smaller than the laser wavelength, \lambda_0) targets. We will mostly consider the case of oblique incidence under \, p-polarization. One of the questions we want to answer is the existence of the ‘transparent’ ion acceleration regime previously observed in simulations at a lower target density, and more generally, to compare simulation results with existing experimental data. In the next section, we will introduce the numerical code that we will use in this paper and stress the constraints associated with simulations at high plasma density. In section 3, we will analyse the quantitative and qualitative changes in laser–plasma interaction as a function of target density. In section 4, we will focus on variations with target thickness, with a particular emphasis on ion acceleration from the rear surface. Variations with other interaction parameters (laser pulse intensity, duration, angle of incidence and polarization) will then be considered in section 5. Section 6 will sum up our findings and discuss their experimental relevance.

2. Model and constraints

Numerical simulations were carried out with the particle-in-cell (PIC) [25] code CALDER [26], in two-dimensional (2D) geometry. Laser–plasma interaction is modelled by solving the coupled set of Maxwell equations for the evolution of the electromagnetic field (incident and self-consistent) and one Vlasov equation for each particle species, specifying how the particle distribution function evolves under the action of the electromagnetic field. All the targets in this paper are modelled as pre-ionized, collisionless hydrogen plasmas. Despite the large target densities considered here, we believe that this is still a reasonable assumption as far as proton acceleration is concerned: due to high electron temperature and small target areal density,
electron collisional effects should be of second order compared to collective mechanisms. Regarding ionization, the large laser or electrostatic fields incident on or generated at the target surfaces should fully ionize hydrogen on a time scale much shorter than the pulse duration. We know that compared to experimental targets, usually a mixture or a sandwich containing protons, the use of purely hydrogen targets can alter the details of the proton spectrum [27, 28] by preventing specific acceleration mechanisms [29]. But this simplification also helps us to focus on the main features of TNSA acceleration, and in most cases we do not expect it to have a strong impact on the peak proton energy, which is our main figure of merit.

Some well-known constraints and limitations of PIC simulations are exacerbated in the context of our study. High plasma density requires small spatial steps, of the order of the plasma electron Debye length. With a longitudinal mesh of $\Delta x = \lambda_0/160$, our simulations do not fulfill this condition initially, but it is verified as soon as hot electrons above a few tens of keV are produced. However, the remaining, unheated electrons have a Debye length smaller than $\Delta x$, and some numerical heating is observed in the simulations, requiring a large number of numerical particles per computation cell, up to several hundred. This is all the more difficult because these simulations have to be run on a large number of time steps, as ion acceleration develops on a time scale longer than the laser pulse duration. Special attention has been devoted to keeping numerical heating low in our simulations, as spurious electron heating would in turn compromise the evaluation of ion acceleration. As an alternative to increasing the number of particles, a second-order particle form factor has been used [30]. Energy conservation is achieved to better than a few per cent of the incident laser energy. The resulting large number of particles, up to 300 million, is distributed over several tens of processors in parallel to speed up the calculation. Even then, a specific constraint arises from our particular subject of study: as we model the evolution of a very thin layer of plasma immersed in a large computation box, efficient load balancing among the processors in the parallel calculation requires that domain decomposition be performed in the transverse direction only.

In all the simulations presented below, the linearly polarized laser pulse is incident from the left of the simulation box, with a wavelength of 0.8 $\mu$m and a Gaussian transverse intensity profile of 4.8 $\mu$m full-width at half-maximum. Ions reaching the system boundaries are absorbed, but electrons are either reinjected with thermal velocity or absorbed, in such a way as to both preserve the global charge neutrality of the system and model cooling down by electrons flowing far from the interaction region.

### 3. Variations with target density

We begin by computing the interaction of a short and intense laser pulse with a sharp-gradient, thin foil at various densities [31]. The foil thickness is $\lambda_0/26.65$, or 30 nm for 0.8 $\mu$m laser wavelength. It is located in a $50\lambda_0 \times 25\lambda_0$ computation box, and is irradiated by a 30 fs duration, $10^{19}$ W cm$^{-2}$ intensity laser pulse at 30$^\circ$ incidence. The laser pulse is polarized in the plane of incidence ($p$-polarization). With these parameters held fixed, the target density is changed from 10 to 150$n_c$. The laser absorption, reflection and transmission rates, as well as peak ion energy, are computed at the end of each simulation and plotted in figure 1. The time at which the simulations are stopped, typically 260 fs after the peak of the laser pulse has hit the target surface (denoted as time $t_0$), is enough to observe fully developed proton acceleration. ‘Constant’ peak proton energies would take a much longer time to reach, but for different interaction parameters

Figure 1. Absorption, reflection, transmission rates, maximum proton energy and energy in hot electrons as a function of target density for a 30 nm target irradiated by a 30 fs, $10^{19}$ W cm$^{-2}$, 0.8 $\mu$m laser pulse at 30° incidence.

the histories are similar enough for us to be confident that the peak proton energies measured at $t_0 + 260$ fs are representative of what they would be at later times.

At $10n_e$, the target provides too little current to prevent pulse propagation through it. More than 80% of the incident pulse energy is transmitted through the foil. Since little energy is coupled to the plasma and the target density falls very rapidly, ion acceleration is rather inefficient: at the end of the simulation, roughly 260 fs after the peak of the pulse has hit the target, the peak ion energy is less than 6 MeV. As its density is increased, the target becomes progressively less transparent and more reflective, reaching almost 80% reflection and less than 1% transmission at $150n_e$. Over this density range, however, absorption remains relatively constant, close to 20%. Nevertheless, the peak proton energy computed at the end of the simulation displays a sharp peak around $28n_e$, reaching more than 10 MeV. Increasing the target density still further, maximum ion energies identical to the lowest density case are obtained, slightly below 6 MeV for a $150n_e$ target. The characteristics of hot electrons driving proton acceleration are actually more different from each other than this similarity in ion energy might suggest: absorption in the dense targets is typically twice as large as that in the $10n_e$ plasma (20% versus 11%), but the fast electron temperature is larger in the lower density case, 0.3 MeV at $150n_e$ versus 0.7 MeV at $10n_e$.

A peak of similar magnitude is observed in the amplitude of the rear-surface electrostatic field, with values close to $2.8 \times 10^{12}$ V m$^{-1}$ for the lowest and highest density cases, versus $4.8 \times 10^{12}$ V m$^{-1}$ for the intermediate density. This confirms the electrostatic nature of proton acceleration for our parameters. According to the isothermal model [19], the driving field is proportional to $(n_h T_h)^{1/2}$, with $n_h$ and $T_h$ being the hot electron density and temperature, respectively. In a first approximation, for fixed target geometry, this product is proportional to the amount of laser energy coupled to plasma electrons shortly after the interaction, i.e. to the absorption rate. Yet no large peak is visible in the absorption curve of figure 1. An attempt to correlate peak ion energy with electron temperature is also in vain, in part because electron distributions can be far from Maxwellian at low density. Instead, a clearer correlation is obtained...
Figure 2. Density of electrons heated to more than 1.5 MeV at 126 fs for three initial target densities (parameters identical to those of figure 1): (a) 10n_c, (b) 28n_c and (c) 150n_c.

with the amount of laser energy coupled to hot electrons (>0.5 MeV), which shows a much greater contrast than the total absorption, as is visible in figure 1. For intermediate densities, 20–40n_c, electron heating to higher energy is made possible by relativistic transparency (in contrast to high densities, which lead to lower hot electron temperatures), and the target provides sufficient areal density for efficient absorption (in contrast to lower densities, which lead to premature target disassembly and high transmission). This combination of high temperature and large hot electron density leads to optimal ion acceleration. Shortly after the peak of the laser pulse, when the electron kinetic energy in the plasma is largest, figure 2 compares the density map of electrons heated to more than 1.5 MeV for three initial target densities. The larger density of hot electrons obtained in the 28n_c case is striking. At larger initial target densities, laser energy is coupled to a larger number of lower-energy electrons, resulting in the same overall 20% absorption, but in less proton acceleration.

Oblique ‘fronts’ of hot electrons are visible in all three plots of figure 2 (note that the laser pulse is incident from the lower left corner in these pictures). In the cases where significant transparency is observed, energetic electrons are found to be located close to the extrema of the laser vector potential, as one would expect for particles that are co-propagating with the transmitted pulse. However, an asymmetric feature is observed in figures 2(a) and (b) with λ_0/2 spacing of the fronts at the centre of the transmitted pulse, but with fronts stretching alternatively in each transverse direction, so that their spacing is λ_0 at the edge of the laser pulse. In contrast to this, the fronts are thinner and quite symmetric in the high density case, figure 2(c), where no laser energy is transmitted. Electron emission along the specular direction is also visible in this case, with the same geometric features.

We observe, as a function of density, the same trends as previously reported as a function of thickness [14]: the thin, overdense plasma is essentially transparent at low density and reflective at high density, both cases leading to similar ion energies. Intermediate densities provide efficient laser–plasma coupling and heating of a large electron population, leading to larger final ion energies by a factor close to two. In experimentally relevant situations, we see
that even 30 nm solid density foils will be too dense and thick to be relativistically transparent at irradiances of the order of $10^{19}$ W cm$^{-2}$, for 30 fs pulses. We therefore do not expect the ‘transparent regime’ of ion acceleration to be observed in these conditions.

For longer laser pulses, the bulk target density should drop to a lower level during the laser pulse, enabling more energy to be coupled to and transmitted through the disassembling target. We can therefore conjecture that the transparent regime of proton acceleration can be reached at high initial densities, provided the laser pulse is long enough. This behaviour was checked in a second series of simulations, with 90 fs laser pulses. The curves in figure 3, corresponding to this case, are indeed shifted to higher densities compared to figure 1. A 50$n_c$ target, through which only 3% of the 30 fs pulse was transmitted, now lets 50% of the 90 fs pulse pass through. This strong change in transmission with pulse duration, even though the laser irradiance is unchanged, underlines that transmission of the 90 fs pulses has less to do with ‘relativistic’ transparency [16] than with increased transmission through a thin target in rapid expansion [17]: as the pulse gets longer, the peak target density drops to a lower value and enables more energy in the tail of the pulse to be transmitted through the profile. Overall, the density range for efficient acceleration is much broader in this longer pulse case: a maximum ion energy of 17.6 MeV is obtained for the 50$n_c$ target, but it is only reduced to 13.4 MeV for the 150$n_c$ target, even though it is no longer in the transparent regime.

Some conclusions can already be made from the first two series of simulations: for the thin target (30 nm) and moderate irradiance ($10^{19}$ W cm$^{-2}$) considered here, relativistic transparency will effectively increase ion acceleration only for very short pulses (30 fs) incident on sub-solid density material (30$n_c$), or for longer pulses ($\sim$ 90 fs) incident on solid density foil ($\sim$ 150$n_c$). In contrast, we do not expect 30 fs pulses incident on solid density targets to be significantly transmitted through the foil and to lead to enhanced ion acceleration. This is in qualitative agreement with the published experimental results [6, 7]. Note also that the improved acceleration observed by Antici et al for ultra-thin solid foils [18] does not contradict this conclusion as this experiment used a long-duration (300 fs) moderate-intensity pulse.
Figure 4. Absorption, reflection, transmission rates and maximum energy of rear surface ($E_{\text{max}}$) and front surface ($E_{\text{front}}$) protons as a function of target thickness for a 150\(n_c\) target irradiated by a 30 fs, 10\(^{19}\) W cm\(^{-2}\), 0.8 \(\mu\)m laser pulse at 30\(^{\circ}\) incidence.

Obviously, ion acceleration is a complex function of the interaction parameters: target density and thickness, laser pulse irradiance, duration, as well as angle of incidence and polarization. The following sections will study the dependence on some of these parameters.

4. Variations with target thickness

In experiments, target thickness is varied rather than density, from tens of nanometres to tens of micrometres at solid density. The 150\(n_c\), 30 nm thick target considered in the previous section was fully opaque to the 30 fs pulse, and so will of course be thicker targets. We can therefore expect peak ion energies from these targets to slightly decrease with target thickness, as is typically observed for conventional, opaque TNSA [14]. For longer pulses, in contrast, transparency can be expected at low target thickness, followed by a transition to opaque TNSA for thicker targets, so that peak ion energy could be a more pronounced function of thickness in this case.

This behaviour is indeed observed in figures 4 and 5, corresponding to the interaction of 30 and 120 fs pulses on 150\(n_c\) targets with thickness ranging from 10 to 800 nm. For the shortest pulse duration, figure 4, improved acceleration is only observed with the 10 nm target, with almost 4% of the pulse energy transmitted through the target but a significant increase in ion energy, reaching close to 7 MeV. For a large range of thicknesses, then, very low transmission and high reflection rates are measured, and the final peak proton energies are consistently between 5 and 5.5 MeV. Finally, for targets with several hundreds of nanometres thickness, little change is observed in absorption, reflection and transmission rates, but the peak ion energy decreases slightly with thickness, down to less than 4 MeV at 800 nm. The peak energy of ions accelerated away from the front surface back to the laser (‘blow-off’ ions) is also plotted in figure 4. A systematic difference of roughly 1.5 MeV is observed in favour of
Figure 5. Identical to figure 4 but for 120 fs pulse duration.

rear surface ions, and it decreases slightly with increasing thickness. The parameters for this series of simulations are similar to those of the experiment by Neely et al [6]. In this work, a peak ion energy of 4 MeV was reported at 100 nm thickness, decreasing to 3 MeV at 1 µm. This trend is consistent with that measured in our simulations, and the difference in absolute peak energies at 100 nm (5.5 MeV versus 4 MeV) can probably be largely explained by the 2D geometry of our simulations. Consistent with the larger computed energy, the laser-to-proton conversion efficiency, measured for forward-accelerated protons above 900 keV, is also larger in the simulations (4% at 100 nm and 2% at 800 nm) compared to the experimental measurement (close to 1% at 100 nm and 0.5% at 800 nm).

For the longer pulse duration of 120 fs, as in the previous section, more laser energy can be absorbed by the plasma and larger ion energies are obtained. Again, a gradual decrease of peak ion energy with thickness is observed in figure 5, similarly to figure 4. In addition, the transparent interaction regime at low thickness is much more apparent, with more than 60% of the incident laser energy transmitted through the 10 nm target. But as observed in section 3, the energy gain that results from this transparency is less dramatic than that for the shorter pulses: for the 30 fs pulse, if we compare the 800 and 10 nm targets, a 70% gain in peak proton energy is obtained with only limited transmission (4%), whereas for the 120 fs pulse, only a 50% energy increase is obtained for the thinnest target compared to the thickest one, even though transmission is 15 times larger (62%). Blow-off ion energies are plotted in figure 5 for the thinnest targets only, and are a lower energy bound only. For these long pulses, the most energetic blow-off ions always exit through the left boundary of the computation box before the end of the simulation and therefore only a lower limit on the front surface ion peak energy can be given. In addition, for the three thinnest targets, there is convincing evidence in the early stage of the simulations that this peak blow-off energy will be lower than the peak rear ion energy, whereas no such observation can be made for thicker targets. We therefore do not know, for these targets, how the front-side ion energy compares to the rear-side one.
5. Variations with laser intensity, angle of incidence, pulse duration and polarization

In the following section, all the target parameters are held fixed (100 nm hydrogen target at 150 $n_c$ density), but the laser pulse intensity, duration, angle of incidence and polarization are varied. Laser absorption, reflection and transmission through the target are always relatively weak functions of intensity. For $p$-polarized pulses, absorption is typically between 12 and 20% for an incidence angle of 30° and 30 fs duration. It decreases to the 5–13% range when the incidence is changed to 5°, and increases to 40–51% for 30° incidence with a longer pulse duration, 120 fs. In all cases, transmission is below 1%, so that the reflection rate by the plasma is essentially one minus the absorption.

The peak ion energy is plotted in figure 6 and is a much stronger function of laser intensity. It varies very significantly over the 20-fold increase in intensity that we consider here. Peak ion energy is only a few hundreds of keV at low intensity and small angle of incidence, but is larger than 20 MeV at $2 \times 10^{19}$ W cm$^{-2}$ in the longer (120 fs) pulse case. These ion energies must be correlated to the hot electron temperature, the definition of which is not trivial: the laser pulse durations are not short enough to assume that electron heating is instantaneous compared to ion expansion. Both have characteristic times of a few tens of femtoseconds. It is therefore not straightforward to define the hot electron temperature unambiguously, as electrons are simultaneously heated by the laser pulse and cool down by energy exchange with the ions. The hot electron temperatures reported in figure 7 were measured at 114 and 252 fs, respectively, for the 30 and 120 fs pulse durations, close to the times when the total electron kinetic energy peaks in the simulations. Three typical spectra are given in figure 8, showing that single-temperature Maxwell–Boltzmann distributions are adequate fits to these curves.

In the short pulse cases, the measured hot electron temperatures are significantly smaller than the ponderomotive temperature \cite{32}. $T_{\text{pond}} = 511(\sqrt{1 + I \lambda^2}/1.37 \times 10^{18} \text{ W cm}^{-2} - 1)$ but
**Figure 7.** Hot electron temperatures for the cases of figure 6, and tentative intensity scalings (see text for details).

**Figure 8.** Hot electron distributions close to the peak of the pulse for three simulations with a laser intensity of $10^{19}$ W cm$^{-2}$.

Also slightly smaller than that derived from Beg’s scaling [33], $T_{\text{Beg}} = 239(\lambda I/1.37 \times 10^{18} \text{ W cm}^{-2})^{1/3}$. A good fit inspired by Beg’s law is actually $T_{\text{fit}} = \theta (\lambda I/1.37 \times 10^{18} \text{ W cm}^{-2})^{0.6} = \theta a_{\theta}^{1/2}$, with $\theta = 126$ keV, $\theta = 99$ keV and $\theta = 232$ keV, respectively, for $(30^\circ, 30 \text{ fs})$, $(5^\circ, 30 \text{ fs})$ and $(30^\circ, 120 \text{ fs})$ pulses. It does not come as a surprise that the ponderomotive potential overestimates the electron temperature here, as interaction occurs with a very dense target [34]. For the longer pulse duration, target expansion can provide lower-density plasma for the laser pulse to interact with, thereby allowing larger absorption and heating to higher temperature. Only in this particular case does the ponderomotive scaling appear to be
relevant—but even then, not in better agreement with the data than a power-law variation as per Beg. Neither is it surprising that the exponent in our power law is significantly different from the one measured by Beg, whose experiment featured much longer pulses under poor contrast conditions [33].

The lower peak ion energies measured at 5° versus 30° can be explained by the lower absorption and electron temperature. The difference between ion energies in these two series for 30 fs pulse duration is relatively small compared to differences in absorption and hot electron temperature. The benefit gained from a longer pulse duration is comparatively much more important, with more than a twofold increase in ion energy between 30 and 120 fs pulses at 30° incidence. Peak ion energy is found to depend mainly on laser energy, e.g. the energy obtained at 30 fs and $1.6 \times 10^{19}$ W cm$^{-2}$ is very close to that measured at 120 fs and $4 \times 10^{18}$ W cm$^{-2}$. This is reminiscent of previous findings [35] where the lower electron temperature obtained for lower-intensity, longer pulses was compensated by the larger laser absorption and longer ion acceleration time obtained for longer-duration pulses. Closer inspection of the calculated distributions shows that beam divergence is not strongly affected by the longer pulse duration, but the laser-to-proton conversion efficiency is almost twice as large in the longer pulse case. The latter observation can be correlated to the twofold difference in laser absorption between 30 and 120 fs pulses reported at the beginning of this section.

A remarkable correlation can be made between hot electron temperature and peak ion energy from the rear target surface and is illustrated in figure 9. Whatever the angle of incidence and pulse duration, a simple linear relation, $E_{\text{max}} \approx 18(T_{\text{hot}} - 71 \text{ keV})$, is a good fit through the data.

The peak ion energy measured from the front surface of the target surface off towards the laser (in the so-called blow-off direction) has also been measured and is plotted with open symbols in figure 6. We observe that there is almost no difference between the front-surface and rear-surface peak ion energies in the longer pulse case, whereas there is a significant difference in the (30°, 30 fs) case and a still larger difference for the smaller angle of incidence. This is a somewhat
surprising result, as one could have expected instead that the shortest laser pulse would lead to the smallest front surface perturbation and hence to a more symmetric acceleration. We believe that the behaviour we observe here is actually a result of the very short laser pulse duration and high intensity: when those two features are combined, the electrons are accelerated so strongly and so rapidly that they do not have time to set up a symmetric cloud around the target, leading to transient charge and field distributions that favour rear surface acceleration. Instead, when the irradiance and temperature are smaller or the characteristic interaction time is longer, this initial imbalance is more limited and of little consequence compared to the symmetric acceleration phase that follows. Note that as the angle of incidence is reduced, so is the effective interaction time, explaining why the asymmetry is more pronounced at $5^\circ$ than at $30^\circ$. Very symmetric acceleration was diagnosed in the experiments of Ceccotti et al [7], and this is consistent with our results as the laser setup they used ($5 \times 10^{18}$ W cm$^{-2}$, 65 fs, and $45^\circ$ incidence) corresponds, in figure 6, to parameters leading indeed to little asymmetry in the acceleration.

In a final series of simulations, we computed the interaction of 30 fs pulses incident on the target at $30^\circ$, but polarized with the electric field out of the plane of incidence ($s$-polarization). Laser absorption in this case is drastically reduced, to less than 1% for all intensities, from $10^{18}$ to $2 \times 10^{19}$ W cm$^{-2}$. Under these circumstances, of course, ion acceleration is negligible: the peak final proton energy is less than 1 MeV in the most intense case. This low absorption is not a systematic feature of $s$-polarization: interaction with a lower plasma density can lead to significant absorption of $s$-polarized pulses [32]. Instead we conclude that the high-density, steep gradient and short pulse duration used in the present simulations lead to the very low absorption measured here.

6. Discussion and conclusions

The observations made in this paper can be compared in some detail to previously published experimental results. In their experiment, Neely et al [6] observe a gradual decrease of proton energy with target thickness, no large gain at small thickness, and no significant transmission of laser energy through the target. Figure 4 is made exactly for the experimental parameters given in [6]: we observe a computed energy only slightly larger than the experimental one, and no roll-off for very thin targets, which may hint at some remaining prepulse effect in the experiment. Similar agreement between calculations and experiments has been reported in [7], even though the incident laser intensity had to be slightly reduced compared to its expected experimental value to find good quantitative agreement with the measured spectra. However, the drop in proton energy at very small thickness (30 nm) later reported by the same group [36] is not observed in our calculations. Similar observations of smaller proton energy at 5–10 nm thickness were made by Henig et al [37] and Kiefer et al [38] in experiments conducted on the Trident laser. The higher pulse irradiance and longer pulse durations considered in these experiments, however, clearly put them out of the realm of applicability of the present study. These results, indirectly, support one of our conclusions, namely that improved ion acceleration using relativistic transparency cannot be obtained with tens of nanometres foil thickness with short-durations (30–60 fs), moderate-intensity ($10^{19}$ W cm$^{-2}$) laser pulses. The benefit of using ultra-thin targets had also been evidenced for long pulse duration and lower intensity by Antici et al [18], although with poorer proton beam quality. Their observations are also in qualitative agreement with our findings, even though the lower intensity and longer pulse duration used in this last experiment are somewhat out of the scope of our present study.
Interaction with $s$-polarized light under high-contrast conditions has already been studied experimentally [7]. The absence of measurable proton acceleration in this experiment is consistent with the drastic drop in absorption and peak proton energy evidenced in our calculations for short pulses and steep target density profiles. This behaviour evidences that the target is initially very overdense and remains so during the interaction, preventing significant absorption. Instead, a much more limited decrease in proton energy is measured when switching from $p$- to $s$-polarization under poor laser contrast conditions [7, 39]. This is readily explained as the laser pulse is no longer fully reflected by the thin solid foil in this case, but instead is partly absorbed by the preplasma, for both polarizations.

The general conclusion that can be made from the various simulations analysed in this paper is that the relativistic transparency-enhanced regime of TNSA, observed at moderate plasma density and high laser intensity [14], can only hold at high density and moderate intensity if the target is thin enough and the laser pulse long enough. Its recent experimental observation [37] is consistent with the present study. We note, however, that in this case [37] as in the work of Antici et al [18], the relatively long pulse duration is responsible for a strong drop in target density before the peak of the pulse reaches the target, easing pulse propagation and efficient coupling to the plasma. Working with shorter pulses makes this effect less efficient and transparency more difficult to achieve. We also observed in our simulations that the relative ion energy gain obtained from this transparent regime becomes smaller as the laser pulse duration is increased.

A final result of our simulations is a very regular scaling of electron temperature with intensity and pulse duration, revealed for oblique incidence and moderate intensity, and a strong correlation between electron temperature and peak ion energy. These relationships, and the fact that higher temperatures and absorption are observed for longer pulse durations, confirm the conclusion published previously [35] that for a given laser energy, optimum ion acceleration is not always obtained at the shortest pulse duration.

References


Mora P 2003 Phys. Rev. Lett. 90 185002
Mora P 2005 Phys. Rev. E 72 056401
Fuchs J et al 2006 J. Phys. IV France 133 1151
Nuter R et al 2008 J. Appl. Phys. 104 103307
Lefebvre E et al 2003 Nucl. Fusion 43 629
Kemp A J and Ruhl H 2005 Phys. Plasmas 12 033105
Drouin M 2009 Thèse de l’Ecole Normale Supérieure de Cachan
Wilks S C 1993 Phys. Fluids B 5 2603
Beg F et al 1997 Phys. Plasmas 4 447
Lefebvre E and Bonnaud G 1997 Phys. Rev. E 55 1011
Carrié M et al 2009 Phys. Plasmas 16 053105
Fukumi A et al 2005 Phys. Plasmas 12 100701