Enhanced ion acceleration in transition from opaque to transparent plasmas

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Abstract
Using particle-in-cell simulations, we investigate ion acceleration in the interaction of high intensity lasers with plasmas which transition from opaque to transparent during the interaction process. We show that the highest ion energies are achieved when the laser traverses the target around the peak intensity and re-heats the electron population responsible for the plasma expansion, enhancing the corresponding sheath electric field. This process can lead to an increase of up to 2x in ion energy when compared with the standard Target Normal Sheath Acceleration in opaque targets under the same laser conditions. A theoretical model is developed to predict the optimal target areal density as a function of laser intensity and pulse duration. A systematic parametric scan for a wide range of target densities and thicknesses is performed in 1D, 2D and 3D and shown consistent with the theory and with recent experimental results. These results open the way for a better optimization of the ion energy in future laser–solid experiments.

1. Introduction
Advances in the development of intense short pulse lasers have led to exciting progress in plasma-based ion acceleration. Production of energetic ion bunches from compact laser–plasma systems have attracted great attention due to the wide range of potential applications, from injectors for conventional accelerators, to proton imaging and oncology [1–6].

Several laser–driven ion acceleration regimes have been explored over the last decade. For a given laser pulse, the target conditions determine the dominant acceleration mechanism(s). In solid density targets the most studied ion acceleration mechanisms, both theoretically and experimentally, are Target Normal Sheath Acceleration (TNSA) [7] and Radiation Pressure Acceleration [8]. However, despite continuous increase in laser energy and power, the maximum ion energy produced has been limited to 70 MeV [9], which together with poor spectral quality is still insufficient for many applications of interest. More recently ion acceleration has also been explored in near critical density plasmas via laser Shock Wave Acceleration [10–15] and Magnetic Vortex Acceleration [16–18], being compatible with high-repetition rate systems and promising a better control over the ion beam properties. An interesting intermediate regime is that of the laser induced relativistic transparency [19–22] where the target is initially opaque but due to electron heating and expansion it becomes transparent during the laser interaction. Promising experimental results have been reported that show an enhancement of the ion energy [23–28]. However, the physical picture responsible for this enhancement and the optimal conditions for ion acceleration are not yet clear.

In this paper, we study laser ion acceleration in relativistic transparency regime where the target is initially opaque to the incident laser but becomes transparent due to fast plasma expansion driven by laser produced hot electrons. We show that for a given laser there is an optimal electron areal density that will produce the highest ion energy in this regime. In order to investigate the details of the process, we have performed fully-relativistic, fully-electromagnetic particle-in-cell (PIC) simulations in 1D and 2D with the code PICLS [29, 30] and 3D with the code OSIRIS [31]. We observed in the simulations that the peak ion energy is enhanced if the laser crosses the
target and re-heats the electrons in the expanding sheath region. In order to optimize this enhancement process we derive a simple theoretical model to predict optimal conditions for ion acceleration in the framework of laser transparency. The theoretical model predicts an optimal electron areal density dependence on laser parameters, \( \frac{n_e}{n_c} L_0(\mu m) \propto T_p^{1/4} \) to produce the highest ion energies. Here, \( n_{e0}, n_{c}, T_0, T_p \) and \( L_0 \) are initial plasma electron density, non-relativistic electron critical density, initial target thickness, laser full-width–half-maximum (FWHM) pulse duration, and laser peak intensity, respectively. We benchmark the analytical model with PIC simulations and find good overall agreement. In particular, the analytical model correctly describes the dependence of optimal areal density on laser parameters such as peak intensity and pulse duration. For example, for presently available high intensity laser systems (\( a_0 \approx 10 \sim 15, \tau_p \approx 100 \) fs) the highest ion energy can be produced either with 50 nm thick, 200\( n_c \) targets or with \( \mu m \) thick, 10\( n_c \) targets, which are yet to be used experimentally. The results from this study will allow for a better design and interpretation of laser–solid experiments focusing on ion acceleration with thin solid density targets.

This paper is organized as follows. In section 2, we present detailed results from a 2D simulation for short pulse laser–solid interaction in the transparency regime. We show that when the laser crosses the target, the peak ion energy is boosted compared to conventional TNSA where the target remains opaque throughout the interaction process. In section 3, we present a simple analytical model to predict optimal conditions for ion acceleration based on the 1D-like expansion of the target. We then compare the analytical model with a 1D, 2D and 3D PIC parameter scan in section 4 and show good overall agreement. Finally, in section 5, we present the main conclusions.

### 2. Ion acceleration in transition to transparent regime

TNSA typically occurs when a laser interacts with a solid density foil. The laser–plasma interaction produces hot electrons with temperature \( T_{hot} \) which escape the target setting up a strong \((\approx TV m^{-1})\) space-charge sheath electric field on the target surface which scales as \( E \propto \frac{T_{hot}}{\lambda_D} \) where \( \lambda_D \) is the characteristic hot electron Debye length \([32–34] \). This sheath electric field accelerates ions which are confined in the expanding sheath electron cloud. The large space charge field in theory can accelerate ions to very high energies, however due to the large ion inertia electrons are pulled back and cool in the process reducing the sheath electric field. A substantial improvement in the ion energy gain would be achieved if the electron energy in the expanding sheath region is continuously replenished rather than the electron–ion interaction progressing as an adiabatic process. This possibility may occur if the target becomes transparent allowing the laser to cross and re-heat the electrons that are driving the expansion in the acceleration region.

We have performed PIC simulations in a 2D geometry in order to confirm this possibility and identify the main aspects of the interplay between TNSA and relativistic transparency in determining the optimal conditions for ion acceleration. The laser is \( p \)-polarized and has a Gaussian temporal profile with a peak intensity \( I_0 \approx 2 \times 10^{20} W cm^{-2} \) \( (a_0 \approx 12) \), here \( a_0 \) is the (dimensionless) normalized laser amplitude \( a_0 = 8.55 \times 10^{-10} \lambda_0(\mu m) \sqrt{I_0(W cm^{-2})} \). The laser wavelength is set at \( \lambda_0 = 1 \mu m \) and focal spot size is 5 \( \mu m \). The total laser pulse duration is 942\( \omega_0^{-1} \approx 500 \) fs, with the FWHM of 521\( \omega_0^{-1} \approx 273 \) fs, where \( \omega_0 = 2\pi c/\lambda_0 \) is the laser angular frequency. The simulation domain is 80 \( \mu m \) in the laser propagation \((x)\) direction and 50 \( \mu m \) in the transverse \((y)\) direction. The spatial and temporal resolution used in the simulations are \( \lambda_0/125 \) and \( 2\pi \omega_0^{-1}/125 \), respectively. The total number of particles per cell is 100. We have also used absorbing boundaries for particles and electromagnetic waves. We note that due to their large mean free path Coulomb collisions are not included and are not expected to affect fast electron dynamics and ion acceleration for the high laser intensities and hydrogen (low-\( Z \)) targets considered in our work. For example, the typical Coulomb mean free path of 1 MeV electrons is >1 cm in hydrogen plasma with electron density of \( \approx 40n_c \), which is much larger than the target thicknesses of interest \((0.1–10 \mu m) \). Previous work [19] has also shown that even with higher \( Z \) targets (Al), no significant differences were found in PIC simulations of the relativistic transparency regime with and without collisions.

For the laser described above we have tested different target thickness conditions for proton acceleration. We illustrate the optimal case, here defined as run A, where the peak proton energy was maximized. In run A, we used a 2.5 \( \mu m \) thick hydrogen target with sharp boundaries and with density of 15\( n_c \). The target is initially cold in the simulation and the front surface of the target is at 20 \( \mu m \) from the left boundary. Figure 1 shows the temporal evolution of the laser–plasma interaction from the 2D PICLS simulation. When the laser starts to interact with the target surface, since the target is initially opaque to the laser, its penetration is limited to the skin depth layer \( l = \sqrt{\gamma_0 e^2/\omega_{pe}} \), where \( \gamma_0 = (1 - \nu_0^2/c^2)^{-1/2} \) is the Lorentz factor of the electrons quivering in the laser field and \( \omega_{pe} \) is the electron plasma frequency given as \( \omega_{pe}^2 = 4\pi e^2 n_{e0}/m_e \). Earlier in the laser interaction (\( t \approx 100 \) fs), while the laser is in its rising edge, we see that the laser has slightly compressed the target front surface (figure 1(a)) and is partially absorbed in the interaction region producing hot electrons mostly via \( \vec{J} \times \vec{B} \) heating [35, 36]. In figure 1(j) we see the characteristic 2\( \omega \) electron bunches from \( \vec{J} \times \vec{B} \) heating spaced at \( \lambda_0/2 \).
This leads to a typical sheath electric field being produced on the vacuum target boundaries (figure 1(d)), and to the acceleration of protons by TNSA (figure 1(g)). As the hot electrons drive the plasma expansion the peak electron density starts to drop and at \( t \approx 248 \) fs (figures 1(b) and (e)) reaches the relativistic transparency condition \([37, 38]\), i.e. the relativistically correct critical density \( n_t \approx \gamma_0 n_e \). At this point the plasma transitions from opaque to transparent. This allows the laser to penetrate through the bulk of the target (figures 1(b) and (c)) and re-heat the hot electrons in the expanding sheath region (figures 1(k) and (l)) resulting in an increase in the peak sheath electric field \( E_x \) on the rear side, as seen in figures 1(e) and (f).

It is also important to note that the group velocity of the laser as it crosses the near critical density plasma, \( v_g = c \sqrt{1 - n_t/(\gamma_0 n_e)} \), can be significantly lower than \( c \), thus allowing the laser to interact for an extended period of time with the expanding structure. This leads to a re-heating of the electrons and allows the enhanced TNSA electric field \( E_x \) to decay slowly as it directly depends on the hot electron temperature. Proton acceleration in such an enhanced TNSA field results in higher peak proton energies compared to the conventional TNSA process where the laser stops at the front surface.

In order to quantify the enhancement of the standard TNSA electric field due to laser penetration and interaction with the expanding plasma, we have performed a similar 2D simulation, hereafter referred to as run B. In this case we use a slightly higher target density of \( 23 n_t \) to insure that the target remains opaque to the laser light during the laser interaction. The target thickness in run B is \( 2 \) \( \mu \)m, such that the areal mass density is only 23\% higher than in run A. It is reasonable to assume that the laser absorption should not be significantly
During the expansion, the thickness of the target evolves as density and thickness. We start by considering a thin one-dimensional step-like density profile. The laser pulse is characterized by the wavelength \( \lambda_0 \) and at rest. Electrons are then heated by a p-polarized Gaussian laser pulse incident on the plasma target. The proton spectrum is observed in both runs but with the peak proton energy twice as high in run A compared to run B, as shown in the inset of Figure 2. In the case of opaque target (run B), the maximum proton energy is \( \approx 40 \text{ MeV} \), consistent with previous experimental results. In the case where the target becomes transparent (run A) the maximum energy reaches \( \approx 95 \text{ MeV} \). This shows that if the laser-target parameters are optimized it is possible to significantly increase the peak ion energy in this regime.

In the simulations, we have observed that the optimal conditions for acceleration (i.e. maximization of ion energy) are achieved if the target becomes transparent when the laser is interacting around its peak intensity. On the one hand, by this time the highest hot electron temperature is achieved, leading to the strongest TNSA acceleration at the rear side of the target. On the other hand, it allows for the transmission of a significant fraction of the laser energy (\( \approx 50\% \)) through the target, which will further heat the electrons, maintaining a strong TNSA field for longer time. If transparency occurs too early in the laser pulse, the TNSA field is weak and the laser crosses without interacting for significant time and heating the expanding electrons. If transparency occurs too late in the laser pulse, only a small fraction of the laser energy will reach the rear side, not allowing for a strong re-heating of the electrons. In the next section, based on this observation, we construct a simple analytical model for the optimal conditions for acceleration in this laser transparency regime.

3. Analytical model

We start by considering a thin one-dimensional step-like density profile for the plasma target with the initial density \( n_{0L} \) and thickness \( L_0 \). The target initially is overdense to the laser pulse and the electrons and ions are cold and at rest. Electrons are then heated by a p-polarized Gaussian laser pulse incident on the plasma target. The laser pulse is characterized by the wavelength \( \lambda_0 \), the FWHM duration \( \tau_p \) and the laser (dimensionless) normalized amplitude \( a_0 \).

For a p-polarized laser \( \gamma_0 \) can also be defined as \( \gamma_0 = \sqrt{1 + a_0^2/2} \approx a_0/\sqrt{2} \) for \( a_0 \gg 1 \). As the laser interacts with the target, electrons are strongly heated and lead to target expansion. For simplicity, we assume a 1D-like expansion where the areal mass density of the target will be conserved

\[
n_{e0}L_0 = n_e L.
\]

During the expansion, the thickness of the target evolves as \( L \approx L_0 + 2 c_s t \), where \( c_s = \sqrt{Z k_B T_{\text{hot}}/m_i} \) is the ion sound speed, \( Z, k_B, T_{\text{hot}} \) and \( m_i \) are the atomic number, Boltzmann constant, fast electron temperature and ion mass, respectively. We consider the average fast electron temperature defined by laser ponderomotive scaling \( k_B T_{\text{hot}} = \left( 1 + \frac{a_0^2}{2} - 1 \right) m_e c^2 \approx \frac{a_0^2}{4} m_e c^2 \).
In order to maximize ion acceleration the target should become relativistically transparent, i.e. \( n_e \approx a_0 / \sqrt{2} n_c \), near the peak of laser intensity (\( r \approx r_p/2 \)) as observed in the simulations discussed in figure 1. In the limit of high laser intensity (\( a_0 \gg 1 \)) (which is the limit of interest for the generation of high energy ion beams), by the time the laser reaches peak intensity the expansion of the target largely exceeds the initial target thickness \( L_0 \). Under this assumption and after substituting \( n_e \) and \( L \) in right side of equation (1), we arrive at an expression for the optimal areal density of the target as a function of the laser parameters

\[
\frac{n_0}{n_c} L_0 \approx \sqrt{\frac{a_0^3}{2}} Z m_e \frac{m_i}{Z m_e} \approx 0.59 \sqrt{\frac{a_0^3}{2}} Z m_e \frac{m_i}{Z m_e}
\]

Equation (2) predicts that there is an optimal electron areal density for a given set of laser conditions (peak intensity and pulse duration) to produce the highest ion energies in the interaction of intense lasers with solid density targets in the laser transparency regime. Note that the validity of this model relies on the fact that the laser vector potential as \( \mathbf{A} \) is the limit of interest for the generation of high energy ion beams.

### 4. Comparison with PIC simulations

In order to test the validity of our model we have performed a wide parameter scan using the 1D and 2D PICLS simulations. We also performed 3D simulations using OSIRIS. Several 1D and 2D tests were performed to compare results from PICLS and OSIRIS for the optimal conditions and consistent results were observed, which has motivated us to use both PIC simulation codes to obtain the complete 1D to 3D parameter scan. In this parameter scan we have changed the laser and target parameters systematically to understand which combination of parameters leads to the highest ion energies and to compare that with the theoretical prediction from equation (2). We have started by doing a large 1D parameter scan, where we varied both target density and thickness, in order to confirm the existence of an optimal areal density. Table 1 shows the peak proton energy observed for different areal densities as function of the target thickness (variation along the column) or density (variation along the row). We considered a Hydrogen target and the densities were varied from \( 6 n_c \) to \( 600 n_c \), whereas the target thickness ranged between \( 10 \) nm and \( 10 \) \( \mu \)m. The laser peak intensity is fixed at \( 1.5 \times 10^{20} \) W cm\(^{-2}\), which corresponds to \( a_0 \approx 10 \). FWHM pulse duration and wavelength are 273 fs and 1 \( \mu \)m, respectively. The peak proton energy obtained in the simulations for each set of varying thicknesses and densities is shown in table 1, with the higher proton energies highlighted in bold. We clearly observe that there is an optimal condition for acceleration that corresponds to fixed areal density, \( n_0/n_c L_0(\mu m) \), which falls along the diagonal of the table. The existence of an optimal areal density is further illustrated in figure 3, where we plot the peak proton energy as a function of areal density for the different cases. We observe that the maximum proton energy is reached for an optimal areal density of \( n_0/n_c L_0(\mu m) \) ≈ 10–24. The difference to our analytical prediction \( (n_0/n_c L_0(\mu m)) \approx 36 \)
is in large part associated with the weak laser absorption in 1D and will be explained below. It is remarkable that this optimal areal density is maintained for such a wide range of thicknesses associated with current laser–solid experiments and that the peak proton energy is approximately the same, and independent of the actual target thickness or density. We note that the focus of this comparison, in particular using 1D simulations, is on experiments and that the peak proton energy is approximately the same, and independent of the actual target thickness. We have tested our model for different target materials. In particular, we have performed 1D PIC simulations for a carbon target overestimate the ion energy. We have tested our model for different target materials. In particular, we have performed 1D PIC simulations for a carbon target to verify the dependence of our model on the target material. For these simulations, we have used a Carbon target of density \( n_c = 100 n_t \) and varied the target thickness from 20 to 200 nm. The laser parameters used in these simulations were \( a_0 = 10 \) and duration \( \tau_p = 110 \text{ fs} \). In the simulations, the carbon ion energy has been maximized at the areal density \((n_c/n_t) L_d(\mu m) \approx 7.5\), which is in good agreement with the optimal areal density predicted by our model, i.e. \((n_c/n_t) L_d(\mu m) \approx 10\).

After confirming the existence of an optimal areal density, we have performed a large parameter scan in 1D, 2D, and 3D in order to understand if its dependence on laser duration and \( a_0 \) is consistent with our analytical predictions. We consider a Hydrogen plasma with solid density \( 40 n_t \) and change the target thickness for (i) different laser amplitudes \( a_0 \), ranging from 5 to 20, while keeping the FWHM pulse duration \( \tau_p = 112 \text{ fs} \), (ii) different FWHM pulse duration \( \tau_p \), ranging from 50 to 500 fs, while keeping the laser \( a_0 = 10 \). The choice of Hydrogen for the plasma target is motivated by the recent development of cryogenic Hydrogen jets at the Matter Under Extreme Condition station at SLAC which can be used for ion acceleration experiments. For Hydrogen, solid density is \( \approx 40 n_t \) for a 1 \( \mu m \) wavelength laser. Hydrogen cryogenic jets with tunable thickness (1–20 \( \mu m \)) provide the opportunity to explore proton acceleration from a pure hydrogen source of solid density. Results from 1D, 2D and 3D PIC simulations are shown in figures 4(a) and 4(b) for \( a_0 \) and \( \tau_p \) dependence, respectively. The error bars, associated with the optimal areal density points shown in the figures 4(a) and 4(b), represent the two adjacent areal densities that are simulated to obtain the optimal areal density at which the ion acceleration is maximized.

We find that for a given laser \( a_0 \) and \( \tau_p \) there is indeed an optimal electron areal density for which the protons have achieved the highest energy during the interaction. The optimal areal density from 1D and 2D simulations follows the same trend as predicted in equation (2). The results from 2D and 3D simulations are in better quantitative agreement with theory. This is mostly associated with the fact that in 1D simulations with a sharp density profile it takes a significant time for the laser absorption and electron heating to increase and the hot electron temperature is underestimated. This also means that the rate of the plasma expansion is underestimated in 1D for a steep plasma profile. Multidimensional (2D and 3D) effects such as surface bending and rippling are known to enhance the laser absorption, which are not present in 1D. In 2D and 3D, we have confirmed that the hot electron temperature is close to the ponderomotive scaling used in the analytical model. It is important to note that for a given laser pulse the optimal areal density is approximately the same (within a factor of 2) in 1D, 2D and 3D. However, the peak proton energy for the optimal areal density decreases with increasing dimensionality of the simulations. The role of the dimensionality on the maximum proton energy is not the focus of the present work and will be presented elsewhere.

We clearly observe that the optimal density increases for either increasing laser \( a_0 \) or pulse duration \( \tau_p \), i.e. it increases with increasing laser energy. Detailed analysis of the simulations confirms that for targets much thinner than the optimal condition the laser penetrates the plasma too early before a significant TNSA field is established. As the laser crosses the target it interacts with the expanding plasma only in a short region and does not provide a significant increase in the proton acceleration. Similarly, for much thicker targets, the laser penetrates the target only later in the falling edge, when most of the laser energy has been reflected/absorbed and
the re-heating of sheath electrons is not efficient. We have also verified in the simulations that for the optimal areal density the laser crosses the target shortly after its peak intensity which appears to be the most important condition. Our results show that in micron-scale Hydrogen jets optimal proton acceleration is achieved for $a_0 \approx 20$.

We have also compared our optimal areal density prediction from equation (2) with previous experimental results for ion acceleration in the transparency regime [25–27], which have shown the evidence of an optimal target thickness for a given laser at which the ion energy has been maximized. In these experiments the targets are initially opaque to the laser and become transparent during the laser interaction due to expansion, consistent with the assumptions of our model. In particular, [25] showed that for a laser pulse with $a_0 \approx 7$ and $\tau_p \approx 700$ fs the optimal areal density is $(n_0/n_c)L_0(\mu m) \approx 25$, and our model (equation (2)) predicts 37. In [26] $(a_0 \approx 19.6$, $\tau_p \approx 160$ fs) the optimal areal density was observed to be $(n_0/n_c)L_0(\mu m) \approx 56$, and our model predicts 40. In a more recent experiment [27] $(a_0 \approx 21$, $\tau_p \approx 500$ fs), $(n_0/n_c)L_0(\mu m) \approx 154$, which is again in a good agreement with our analytical prediction of 141. Note that the analytical model has a dependence on the target material, therefore the analytical estimates presented above take into account the ion species (target material) used in the different experiments.

We note that the scaling results obtained in our simulation, which are consistent with our theoretical model and with recent experiments, are different from other scalings obtained by different groups. Previous works obtained scalings for optimal ion acceleration mostly by fitting the PIC simulation results [20, 39, 40]. In [20, 40] the parameter range used extended beyond the relativistic transparency regime considered in our work, and thus their scaling covered different acceleration regimes. Reference [39] considers the transition to the Direct Coulomb Explosion regime, where the optimal condition for ion acceleration is defined when the relativistic skin depth becomes comparable to the initial target thickness, as described in [41]. It is thus not surprising that the scalings obtained in our work for the relativistic transparency regime differ from these previous results.

5. Discussion

In conclusion, we have shown that optimal ion acceleration can be achieved when the target becomes relativistically transparent at the peak intensity of the laser pulse interaction. This allows the remaining fraction of the laser to cross the target and re-heat the electrons, enhancing the sheath field at the rear side of the target. We have derived a simple analytical model that shows that for a given set of laser conditions there is an optimal target areal density to produce the highest energy ions in the laser transparent regime. This optimal areal density scales as $\tau_p^{1/4}$, which is in very good agreement with multidimensional PIC simulations. We also show that for a given laser this optimal areal density remains fairly constant over a wide range of target densities and
thicknesses. To date, most of the experimental work exploring ion acceleration in the relativistic transparency regime used high density nanometer thick targets [26]. Our results show that it is possible to obtain similar acceleration mechanisms by using lower density and thicker targets such as micron-scale Hydrogen jets, which are compatible with high-repetition rate laser systems. These findings open the possibility to achieve significantly higher proton energies in the future by appropriately matching the laser and target parameters.

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