Target shape effects on monoenergetic GeV proton acceleration

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Abstract. When a circularly polarized laser pulse interacts with a foil target, there are three stages: pre-hole-boring, hole-boring and light sail acceleration. We study the electron and ion dynamics in the first stage and find the minimum foil thickness requirement for a given laser intensity. Based on this analysis, we propose using a shaped foil for ion acceleration, whose thickness varies transversely to match the laser intensity. Then, the target evolves into three regions: the acceleration, transparency and deformation regions. In the acceleration region, the target can be uniformly accelerated producing a mono-energetic and spatially collimated ion beam. Detailed numerical simulations are performed to check the feasibility and robustness of this scheme, such as the influence of shape factors and surface roughness. A GeV mono-energetic proton beam is observed in three-dimensional particle-in-cell simulations when a laser pulse with a focus intensity of \(10^{22} \text{ W cm}^{-2}\) is used. The energy conversion efficiency of the laser pulse to the accelerated proton beam with the simulation parameters is more than 23%.

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1. Introduction

Ion acceleration is one of the most important topics in the ultrashort ultraintense (USUI) laser-plasma accelerator field [1]–[4]. Because the laser-accelerated proton and ion beams are highly concentrated, ultrashort and ultraintense, they have a broad spectrum of potential applications, such as proton therapy [5], proton imaging [6, 7], ion beam ignition of laser fusion targets [8], etc. These applications usually require a high degree of beam monochromaticity as well.

The usual energy spectrum of the ion beams produced due to the mechanism of target normal sheath acceleration (TNSA) shows an exponential decay up to a high energy cutoff. To overcome this, a few schemes are proposed such as the use of a plasma lens [9, 10], double layer targets [11] and special target shaping [12]–[15].

It was shown recently in theoretical analysis and numerical simulations that when a circularly polarized (CP) pulse is used, high-energy mono-energetic ion acceleration can be achieved. The reason is the absence of the oscillatory term in the ponderomotive force of a CP pulse and thus suppression of electron heating [16]. A CP laser pulse gently pushes the whole electron fluid and generates a moving local charge separation field that accelerates ions. It looks as if the whole target is accelerated by the laser radiation pressure. The mechanism then is similar to the radiation pressure-dominated acceleration (RPDA) previously proposed by Esirkepov et al [3]. However, the threshold for the laser intensity is dramatically reduced when a CP pulse is used. In the one-dimensional (1D) geometry and if the laser pulse is long enough, the target can be accelerated in multistages and in every stage the accelerated ions gain the same energy. The narrow width of the final energy spectrum is the result [17].

By using an ultrathin target Klimo et al [18], Robinson et al [19] and Yan et al [20] recently restudied the mechanism. They showed that ions are accelerated continuously and rotate in the phase space. This can be considered as a special kind of multistage acceleration [21]. The second stage begins before the end of the first one. The width of the spectrum is further reduced and mono-energetic ion beams are easily observed. The process is sensitive to a laser prepulse as it might break the ultrathin target and cause pre-plasma to destroy the accelerating structure. Because of the development of USUI laser pulses and plasma mirror technology, this can be controlled in today’s experiments. By the use of a double plasma mirror, Henig et al [22] recently reported the successful achievement of a ps-timescale pulse contrast of $10^{12}$ with peak intensity of $9 \times 10^{19}$ W cm$^{-2}$. The community is still looking forward to getting such high contrast for a higher laser power density such as $10^{22}$ W cm$^{-2}$. From the theoretical side,
Qiao et al. [23] recently studied this kind of acceleration and separated it into two different processes: hole boring and light sail. They noticed the importance of the transition between these two processes to reach the final mono-energetic spectrum. In the hole boring process, the laser pulse propagates through the bulk of the foil target and compresses it. Afterwards, when the compressed layer arrives at the rear side of the foil, the light sail process begins. At this stage, there is no fresh rest plasma in front and the laser pulse is still not strong enough to be transmitted through the compressed target. Despite the internal field, the whole target (electrons and ions) is pushed forward by the laser pressure. Its dynamics can be well described using a ballistic equation [24]. There is a minimum target thickness for the target to stay opaque so that the process can operate. To obtain the minimum target thickness for acceleration, all of the earlier works use the balance between the laser pressure and the charge separation field and assume immobile ions during the balance build-up. This is correct when the laser intensity is relatively small and the target density is low. However, it overestimates the minimum target thickness when the laser intensity and target density increase.

In this paper, we study the process of balance build-up and name this process a pre-hole-boring process. We consider the finite ion mass to calculate the minimum foil thickness for ion acceleration, which is usually also the optimal thickness. Then, we suggest using a shaped target to achieve uniform acceleration. For shaped targets, we find that the acceleration structure (the plasma bunch accelerated by RPA) can be kept for a longer time compared with the usual flat targets. The final spectrum contains a mono-energetic peak. Later we study the robustness of our scheme by considering the influence of the shape parameters and surface roughness on the final spectrum. This lends a detailed description to our recently published paper [25]. Finally, we give some discussions and a summary.

2. Pre-hole-boring and optimal target thickness

Here, we study electron and ion dynamics during laser impinging. When the laser pulse arrives at the front surface of the target, electrons are accelerated and piled up by the laser pressure. Later, ions start to move, being accelerated by the charge separation field. We call this stage pre-hole-boring because during this time ions have not caught up with the compressed electron layer (CEL), and the hole boring process has not yet reached its stationary stage.

For convenience we use normalized variables. The laser electric field is normalized as $a = eE/m_0\omega c$, and spatial and temporal coordinates are normalized by the laser wavelength $\lambda$ and period $2\pi/\omega$, respectively. The particle velocity, mass and plasma density are normalized by light speed in vacuum $c$, electron mass $m$ and critical density $n_c = m\omega^2/4\pi e^2$, respectively.

If we consider only the ponderomotive force of laser pulse acting on plasma electrons (light pressure), the dynamics of the CEL is governed by the equations

$$n_0 l_1 \frac{d\gamma \beta}{dt} + n_0 \gamma \beta \frac{dl_1}{dt} = \frac{a_0^2(t)}{\pi} \frac{1-\beta}{1+\beta} - \pi n_0^2 l_1 (l_1 + l_e),$$

(1)

$$\frac{dl_1}{dt} = \beta,$$

(2)

where $\beta$ is the normalized velocity of the CEL, $\gamma$ is the relativistic factor, $l_1$ is the displacement of the CEL, $n_0$ is the initial plasma density, $a_0(t)$ is the amplitude of the laser electric field and $l_e$ is the thickness of the CEL. The second term on the left side of the first equation comes from
the mass increase of the CEL. The first term on the right side is the contribution of the laser pressure and the second one is due to the charge separation field.

We treat ions as a hydrodynamical fluid and solve the following normalized hydrodynamical equations:

\[
\frac{\partial n}{\partial t} + \frac{\partial (n\beta_i)}{\partial x} = 0, \tag{3}
\]

\[
\frac{\partial \beta_i}{\partial t} + \beta_i \frac{\partial \beta_i}{\partial x} = \frac{2\pi}{m_i} E_x, \tag{4}
\]

\[
\frac{\partial E_x}{\partial x} = 2\pi (n - n_e), \tag{5}
\]

where \(n\) is ion fluid density, \(\beta_i\) is its velocity, \(m_i\) is ion mass and \(E_x\) is charge separation field. The density distribution of electrons \((n_e)\) is calculated from the evolution of the CEL. We simply assume that electrons from the front target are piled up, compressed and uniformly distributed within a region with the size of \(l_e\). We do this because the CEL is always in front of the accelerated ions at this early stage. This assumption will become invalid as soon as the ions catch up with the CEL. Our calculation ends before this time and ensures that the hydrodynamic velocity of the ions at the density peak point is larger than the CEL velocity. The moving distance of the CEL at this time is just the one we are looking for and equals the minimum thickness of the target for ion acceleration \((l_{\text{hydro}})\). As we will see, usually this gives a smaller value than the one \((l_{\text{immo}} = a/\pi n)\) obtained in the immobile ion model. The thickness of the CEL \((l_e)\) is a variable that is difficult to obtain. Usually in a simple model, one assumes that it equals the skin length \([20]\). However, from particle-in-cell (PIC) simulations (for example, see figure 3 in \([26]\)) we see that the real thickness is far less than the skin length. We improve this by considering the relativistic motion of the CEL. It corresponds to the skin length of a moving plasma \(l_s = l_{s0} \sqrt{p_\perp/Y_x}\). Here \(l_{s0} = c/\omega_p\) is the normal non-relativistic skin length; \(p_\perp\) is the normalized transverse momentum of the electrons in the CEL and \(\gamma_x = 1/\sqrt{1 - \beta_x^2}\), with \(\beta_x\) the longitudinal velocity of the CEL.

We solve the system of equations (1)–(5) numerically. In our calculations, we vary the ion mass, target density and laser intensity to see their effects on the minimum target thickness. The foil is assumed to be thick enough initially \((0.2\lambda < x < 1.8\lambda)\) for ions to catch up with the CEL. The electron and ion density distributions at the calculation end are shown in figure 1(a). The density distributions also indicate one of the necessary criteria to end our calculation: the time \((t_{\text{end}})\) when the peak of the ion density distribution reaches the CEL. After this the charge separation field for CEL will deviate obviously from the one used in equation (1). The moving distance of the CEL at this time \((t_{\text{end}})\) is assumed to be the minimum thickness of the target \(l_{\text{hydro}}\) since the ions can catch up with the CEL once the target is thicker than \(l_{\text{hydro}}\). Obviously we can obtain \(l_{\text{hydro}}\) from the numerical calculations shown in figure 1(a). It can also be obtained from the force balance as we will show in the following. Figure 1(b) shows the ratio of the CEL velocity \((\beta_e)\) at the end of the calculation to the theoretical relativistic hole boring velocity \(\beta_h = a/(a + \sqrt{m_i\rho_0})\) \([27]\). As we see, the value tends to a constant. Having this constant value, it is then easy to calculate the displacement of the CEL at \(t_{\text{end}}\) from the relationship of the almost balance between the charge separation force and the laser pressure:

\[
\pi n_e^2 \rho (l_x + l_e) = \frac{a_0^2}{\pi} \frac{1 - \beta_e}{1 + \beta_e}. \tag{6}
\]
Figure 1. Analytical results for the pre-hole-boring process. (a) Density distribution of electrons and ions at the end of numerical calculation. The electron density shows the CEL structure in the front part of the target. (b) Dependence of final velocity of the CEL at the end of the calculation on laser intensity and target density. (c) Evolution of CEL velocity and forces on the CEL along with CEL displacement ($l_1$). Here $F_1$ (the black solid line) indicates the force due to laser pressure, $F_2$ (the red dotted line) indicates charge separation force and $F_3$ (the blue dashed line) indicates force due to mass increase. (d) CEL displacements at the end of the calculation for different ion masses and laser intensities. The black solid line represents the minimum thickness obtained in an immobile ion model.

The force balance can be seen from figure 1(c). The black solid line indicates the force due to laser pressure ($F_1$), the red dotted line indicates the charge separation force ($F_2$) and the blue dashed line indicates the force due to mass increase ($F_3$). The first two forces balance each other very quickly once the CEL moves 0.1λ into the target. The displacements of the CEL obtained in figure 1(a) fit well with those obtained from the force balance calculation. The former is shown in figure 1(d) for different ion masses. The value usually used based on the immobile ions model $l_{\text{immo}}$ is also shown with the black solid line. As we see, when the intensity of the laser electric field is larger than $a_0 = 100$, the present results $l_{\text{hydro}}$ are smaller than the value based on immobile ions $l_{\text{immo}}$. The lighter the ion mass, the larger the difference with the one of the immobile ion model. $l_{\text{hydro}}$ is just the minimum thickness of the foil target for ion acceleration. When the target is thinner than this minimum value, ions cannot catch up with the electrons and neutralize them. Then electrons are smashed away from the ions completely by the light pressure and the target is transparent to the laser thereafter. The electrons are dispersed by the pulse and the naked protons experience Coulomb explosion. The stable RPA acceleration structure disappears. From the present calculation, we see that ions have already caught up with the electrons before the CEL moves a distance of $l_{\text{immo}}$ and the CEL will not completely separate from the ions. So our model shows that the usual value $l_{\text{immo}}$ overestimates...
the minimum thickness. This finding is important for the selection of the target thickness for the multicascade ion acceleration scheme recently proposed by Gonoskov et al [28].

3. Ion acceleration by use of a shaped foil target

Up to now we have discussed the minimum target thickness for ion acceleration in the laser pressure-dominated regime. Once the target is thicker than the minimum value, the whole target is opaque to the laser pulse and is accelerated in a hole-boring process with velocity $\beta_h$. When the CEL arrives at the rear of the foil, the acceleration changes to a light sail process. Then, the momentum evolution of the target satisfies [19]

$$\frac{dp}{dt} = \frac{2I}{c} \sqrt{p^2 + \sigma^2 c^2} - p,$$

(7)

where $I$ is the laser intensity and $\sigma$ is the target area density. For the velocity evolution of the target, one obtains

$$\frac{d\beta}{dt} = \frac{1}{2\pi n_0 m_i c} \frac{E^2(t, x, r)}{l_0} \frac{1 - \beta}{\gamma^3 (1 + \beta)}.$$  

(8)

Here $E$ is the laser electric field amplitude, and $n_0$ and $l_0$ are the target initial density and thickness, respectively.

Equation (8) shows that the energy spread of accelerated ions depends on the transverse variation of the local ratio of laser intensity to the target area density. The distance the ions pass under the laser pressure is $s(r) \propto E^2(t, x, r)/l_0^{-1}$. An initially flat target is inevitably deformed, if the laser intensity is not uniform transversely. The target deformation quickly destroys the acceleration structure and deteriorates the beam quality. From equation (8), we see that a target can be uniformly accelerated if its areal density $\sigma = n_0 l_0$ is shaped properly. For the usual transversely Gaussian pulse $[a = a_0 \times \exp \left(-r^2/\sigma_T^2 \right)]$, one can use a target with the Gaussian thickness distribution as shown in figure 2. In the following simulations, the distribution of the target thickness along the transverse direction is

$$l = \max\{l_1, l_0 \times \exp \left((-r^2/\sigma_T^2)^m \right)\}.$$  

(9)

Here $r$ is the transverse distance to the laser axis, and $l_1, l_0, \sigma_T$ and $m$ are the shape factors, which are marked in figure 2.

Before carrying out simulations for this kind of shaped target, we first check the target transparency for the pulse with a transversely Gaussian pulse. In figure 3, we show the minimum thickness requirement from theoretical calculation by use of equation (6) and the acceleration factor $F_{\text{acc}} = a^2/l$ in the target transverse direction. $\beta_c$ is the function of $a, n, m_i$. The shaped target thickness and flat target thickness distributions are also shown in the figure. As we see from figure 3(a) for the shaped target, in the center it is thicker than the minimum value $l_{\text{min}}$. At this region, the acceleration factor $F_{\text{acc}}$ is also almost uniform, so the target can be accelerated uniformly. Outside this region, the target thickness is thinner than $l_{\text{min}}$. The target is transparent to the laser pulse here, and ions cannot obtain an effective uniform acceleration. In the outside region, the target is thicker than $l_{\text{min}}$ again and $F_{\text{acc}}$ decreases with radius, so in this region the target is opaque and will be accelerated and deformed. However, for the usual flat target (see figure 3(b)), the target thickness would always be larger than the minimum value; hence it is
Figure 2. Layout of the interaction scheme. $\sigma_T$ defines the transverse Gaussian profile of the shaped target, $l_0$ is the maximal target thickness while $l_1$ is the cutoff thickness. A CP laser pulse is incident on the foil target from the left boundary.

Figure 3. Target partitions in the cases of (a) shaped target and (b) flat target, according to the transparency calculation. The parameters for the shaped target are $l_0 = 0.3\lambda$, $l_1 = 0.1\lambda$, $m = 1$ and $\sigma_T = 6\lambda$. For the flat target we just use $l_1 = l_0 = 0.3\lambda$. The laser pulse has a focus of $\sigma_L = 8\lambda$. The red solid line represents the target thickness distribution along the transverse direction; the blue dashed line represents the minimum target thickness requirement for an opaque target. The black line represents the acceleration factor.

opaque to the laser pulse and the whole target belongs to the deformation region. Or the target would be transparent in the central region and opaque in the outside region, and the acceleration is also not effective. We will demonstrate these regimes in the following PIC simulations.
By using equation (6), we can also obtain the final size of the accelerated ion bunch in the target center. For the present target shape the calculated bunch radius is
\[ r_b = \sigma_L \sigma_T \sqrt{\ln[\pi n_0 l_0 a_0^{-1}/(1 + \beta_e)/(1 - \beta_e)](\sigma_L^2 - \sigma_T^2)^{-1}}, \]
where \( \beta_e = \alpha \beta_h \) and \( \alpha \) is a function of ion mass and laser intensity. Theoretically it can be obtained from figure 1(b) in which \( \alpha \approx 0.8 \). However, in the PIC simulations we find that the accelerated bunch size can be approximated much better when we choose \( \alpha \approx 1 \). This difference may result from our over-strict criterion for the minimum target thickness. From the calculated bunch size we can also obtain requirements for the shape factors, such as \( \sigma_T < \sigma_L \) and \( l_1 \leq l_0 \times \exp(-r_b^2/\sigma_T^2) \). In the next section, we present the results of multi-dimensional PIC simulations, compare them with the above results and use them to obtain the optimal shape factors.

3.1. PIC simulations

We use the VLPL code to do both 2D and 3D simulations [29]. First, we perform 3D simulations to show the ion acceleration from the shaped foil target and then we investigate in detail the effects of the target parameters on the beam quality by less time-consuming 2D simulations.

The simulation box in the 3D simulation is \( 25\lambda \times 27\lambda \times 27\lambda \), which consists of \( 2500 \times 225 \times 225 \) cells. A CP laser pulse with a Gaussian profile in space and a trapezoidal profile (linear growth–plateau–linear decrease) in time is normally incident on the foil target. The temporal profile satisfies
\[
a(t) = a_0 \exp\left(-\frac{y^2}{\sigma_L^2}\right), \quad 0 \leq t < T,
\]
\[
a(t) = a_0 \exp\left(-\frac{y^2}{\sigma_L^2}\right), \quad T \leq t \leq 6T,
\]
\[
a(t) = a_0 \exp\left(-\frac{y^2}{\sigma_L^2}\right)(8 - t), \quad 6T < t \leq 7T,
\]
where \( a_0 = 100 \) is the normalized intensity of the laser electric field, \( \sigma_L = 8\lambda \) is the focal spot radius and \( T = 3.3 \) fs is the laser cycle for an infrared laser with 1 \( \mu \)m wavelength. The target plasmas are composed of electrons and protons and they are initially located between \( x = 2.0\lambda \) and \( 2.3\lambda \), with a transversely varying thickness, as shown in figure 2. Here, the cutoff thickness \( l_1 = 0.15\lambda \) and \( \sigma_T = 6.0\lambda \). The plasma density is \( n_0 = 100 \).

Figures 4(a) and (b) present the proton density distributions at two time points: \( t = 15T_0 \) and \( 20T_0 \). One sees that the center part of the target is accelerated strongly and soon breaks away from the whole target. As expected, the deformation of the target center is well suppressed and a peak appears in the proton energy spectrum, which is shown in figure 4(c). We find that a total of 49.8% laser energy has been transported to particle energy: 39.5% to protons and 10.3% to electrons. The number of protons whose energy is larger than 0.65 GeV is about \( 8.3 \times 10^{11} \) and their total energy is about 120 J. Instead, for a usual flat target, the energy spectrum shows a typical exponential decay due to the easy heating and deformation of the target. By diagnosing the divergency angle distribution, the average divergency of these energetic protons from the shaped foil target is less than 5°. The whole target can be stably accelerated until the end of laser irradiation with the energy conversion efficiency as high as 23.1%. However, we should point out that this conversion efficiency is possibly optimistic. As we know, the
Figure 4. Proton density distributions in 3D simulations at $t = 15T_0$ (a) and $20T_0$ (b). The single-headed arrow indicates the high quality proton bunch with a higher energy and better collimation. The initial target with $\sigma_T = 6\lambda$ is located between $x = 2.0\lambda$ and $2.3\lambda$, irradiated by a CP laser pulse with $\sigma_L = 8\lambda$. (c) Proton energy spectra at $t = 20T_0$. Here, the normal flat target with $l_0 = l_1 = 0.3\lambda$ is located at the same position as the shaped foil target and is irradiated by the same laser pulse.

The instant laser absorption rate is proportional to $2\beta/(1 + \beta)$, where $\beta$ is the target velocity [26]. Obviously if the target is lighter, the absorption rate is higher. Due to the limitation of the current computational resource, the electron density of the simulation target ($100n_c$) is lower than the real target ($>500n_c$) presently used in experiments. And the target composition (hydrogen) is lighter than the target usually used (carbon and hydrogen). So, the present simulation may give an overestimated conversion efficiency than the real experiment. However, the improvement of the acceleration structure and final ion spectrum by the use of a shaped target compared with a flat one is demonstrated.

In figures 4(a) and (b), it is easy to distinguish the deformation region, acceleration region and transparency region. The center part is the acceleration region, which composes the energy peak in the spectrum. Around it is the transparency region, where the electron density is quickly low enough so that the laser pulse can easily penetrate it and then go through it. This region separates the acceleration region from the deformation region located in the outer side of the target and effectively suppresses the target heating and protects the acceleration region. For a flat target, this transparency region can also be formed due to the density dilution during target deformation. However, the process is much slower and it is a gradual change. Target heating is inevitable, and there is no obvious acceleration region formation. The pre-shaped target makes the final isolated acceleration bunch possible. The radius of the bunch in our simulation is around $3.1\lambda$, which is close to the theoretical estimate for $r_b \approx 3.5\lambda$.

Although our 3D simulations show the possibility of a GeV monoenergetic proton beam acceleration, a well-shaped target is required. In experiment, it may be difficult to make a well-matched target without any deviations. Certainly, the final beam quality should be related with
the target shape factors. For real applications, we are going to demonstrate the robustness of this shaped target scheme. In the following, we discuss in detail the effects of these factors on the final beam bunch. To save computational time, we only perform 2D simulations to show the effects. A series of 2D simulations have been performed. The whole simulation box is $32\lambda \times 32\lambda$, sampled by $3200 \times 3200$ cells. The foil target initially locates between $x = 5.0\lambda$ and $5.3\lambda$. The CP laser pulse has the same profile in both time and space as the above 3D case except that the pulse duration is now $\tau = 10$, which corresponds to a distribution of 1T-8T-1T in time (see equation (10)--(12)).

3.2. Dependence on shape factor

We first take into account the influence of cutoff thickness $l_1$ on beam quality. In the simulation we fix all other parameters and only change $l_1$. The ratio of target width to laser focus ($\sigma_T/\sigma_L$) is kept as 7/8. Figure 5 shows the simulation results. We can see that the spatial energy distributions in figures 5(a) and (b) are almost the same. The cutoff thicknesses for these two cases are $0.05\lambda$ and $0.15\lambda$, respectively. The corresponding energy spectra are shown in figure 5(d). Again, the energy distributions of high-energy protons for these two cases are the
Figure 6. Proton energy distributions in $x$–$y$ space for different $\sigma_L$ and $\sigma_T$ at $t = 30 \tau_0$: (a) $\sigma_L = 6\lambda$, $\sigma_T = 6\lambda$, (b) $\sigma_L = 8\lambda$, $\sigma_T = 6\lambda$, (c) $\sigma_L = 12\lambda$, $\sigma_T = 6\lambda$ and (d) $\sigma_L = 12\lambda$, $\sigma_T = 10\lambda$. Corresponding proton energy distributions as a function of divergency angle are shown in (e)–(h).

same. However, when $l_1$ is increased to $0.25\lambda$, the energy spectrum changes significantly as shown in figure 5(d). The peak energy decreases and the cutoff energy increases. The spectrum tends to be that of a flat target. It shows that there exists a threshold value for $l_1$. When $l_1$ is larger than the threshold, the spectra are significantly different. In additional simulations, we find that the threshold is about $0.20\lambda$ in the present case. This is close to the theoretical value of our analysis above. When the cutoff thickness is smaller than $l_0 \times \exp(-r_b^2/\sigma_T^2)$, the accelerated bunch size is almost constant as shown in figures 5(a) and (b). When it increases, no obvious transparency region separates the acceleration and the deformation regions. Target deformation happens continuously along the target and the effectively accelerated bunch is smaller as shown in figure 5(c) and the final spectrum is close to the flat target case.

The most important factors are the matching parameters: $\sigma_T$ and $\sigma_L$. In the following we check their effects on beam quality. Figure 6 shows some typical simulation results for different $\sigma_T$ and $\sigma_L$. The top four figures show the proton energy distributions in space while the bottom four correspond to the angular distributions. We fix $\sigma_T = 6\lambda$ and increase $\sigma_L$ from $6\lambda$ to $12\lambda$. It is shown that when $\sigma_T$ is close to $\sigma_L$, target deformation happens. Most protons are located at the deformation region and the target evolves into a natural cone. The corresponding energy-divergency distribution is widely spread, as shown in figure 6(e). With the increase of laser focus, the center part of the target is uniformly accelerated so that it can break away from the whole target. The three regions mentioned before can be easily distinguished from figures 6(b) and (c). A bunch of protons with higher energy and better collimation is formed in figures 6(f) and (g). The radius of the bunch decreases with $\sigma_L$, which confirms the theoretical analysis. When $\sigma_L$ increases, the transparency region extends to the target center, and a larger laser focus (or laser energy) leads to a smaller accelerated bunch. The results show the importance of a well-matched target. Figures 6(d) and (h) correspond to a well-matched case when the laser focus is $\sigma_L = 12\lambda$. When we increase the target width close to the $\sigma_L$, the acceleration region broadens and more ions are uniformly accelerated.

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Figure 7. Proton energy spectra (a) and divergency angle (b) distributions for different laser focus radii $\sigma_L$ and $\sigma_T$ at $t = 30T_0$.

Table 1. Available and optimum values of $\sigma_T/\sigma_L$.

| $\sigma_L$ | $\sigma_T/\sigma_L$ | Available values | Optimum |
|---|---|---|---|
| 6 | 0.5 | 0.583 | 0.75 | 0.833 | 0.916 | 0.75 |
| 8 | 0.375 | 0.5 | 0.6 | 0.75 | 0.8125 | 0.875 | 0.8125 |
| 10 | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 | 0.8 |

Figure 7 shows both the energy spectra and the angular distributions for these cases. As expected, there is a clear quasi-monoenergetic peak in the case with $\sigma_T/\sigma_L = 6/8$ and $\sigma_T/\sigma_L = 10/12$. The peak energy is about 0.85 and 0.80 GeV, respectively. The corresponding full-width at half-maximum divergency angle is about 6° and 4°. Obviously, for the well-matched cases the larger the laser focus, the more protons are accelerated. In contrast, for the imperfectly matched case, both the peak energy and the total production of accelerated protons decrease. For the unmatched case, no clear peak appears and the proton number decreases further.

In order to obtain the optimal ratio of $\sigma_T/\sigma_L$ in the simulation, we perform the parameter scan as shown in table 1. Here, all the target and laser parameters are the same except for $\sigma_T$ and $\sigma_L$. The available values of $\sigma_T/\sigma_L$ mean that a high quality proton bunch with a quasi-monoenergetic peak and low divergency angle can be observed with these parameters. The optimum value indicates the best bunch quality such as the narrowest energy spread and the lowest divergency. It is shown that the tolerable values of $\sigma_T/\sigma_L$ exist around 0.50–0.90 while the optimum value is about 0.80. These simulations supplement our analytical results, which only give the condition of $\sigma_T/\sigma_L < 1$ and also give some quantitative illumination to the experiments.

3.3. Effect of target surface roughness

Since in our scheme, the target thickness is less than the laser wavelength, i.e. nanometer thickness, the relatively larger surface roughness of the target might be inevitable in real experiments and may influence the final accelerated ion beam. Here we check its effects by comparing three simulations with different surface roughness: (a) a smooth surface, (b) 10%
roughness and (c) 30% roughness. In our simulation, the roughness is completely randomly selected, which is close to a real target. It means that there are is no 'typical wavelengths' of the surface modulation as shown in figure 8(a). The amplitude of the roughness just means perturbation as a fraction of target thickness. In the simulation, we randomly selected the left boundary of the plasma within the modulation amplitude along the transverse direction. The left boundary coordinate is \( x_r(j) = x_s(j) - a \times f(j) \); here \( a \) is the modulation amplitude of the roughness and \( f(j) \) is a random value within \([0,1]\), \( j \) is the label of the cell in the transverse direction and \( x_s(j) \) is the left boundary of a smooth target. The minimum undulation length of the roughness in the transverse direction is the cell length, which is \( 0.01\lambda \).

In order to resolve surface roughness, both the longitudinal and transversal cell sizes should be small enough, which leads to extremely small steps in both space and time in the simulation. This makes the simulations extremely time consuming. Therefore, we only present the simulation results at the early time \( t = 10T_0 \). This time is, however, already long enough to see the final effects. Figure 8(c) shows proton energy spectra for these cases. We notice that all the spectra show a clear energy peak despite the different surface roughness. Yet, for the target with 30% surface roughness, the peak energy is about 0.25 GeV, which is higher than the value of 0.2 GeV in cases with a lower roughness. Similarly, the cutoff energy is also higher than the other two cases. The differences between the two lower roughness cases are
much smaller. The main effect of the target roughness is to increase the laser absorption and conversion efficiency of its energy to superhot electrons. These electrons are easily dispersed in space and initiate the TNSA acceleration. This can be seen in figure 8(b), in which the energy spectrum of the electrons is shown. Obviously the target with 30% roughness has a much higher electron temperature. The other two cases are similar. In addition to the spectrum, we also check the angular distribution. The results are shown in figure 8(d). There is no obvious difference with the case of a smooth target and a target with 10% roughness. So generally speaking, the simulation shows that a roughness of 10% is acceptable. It gives a quantity guide for experimental demonstrations.

4. Discussion and summary

We should point out that target shaping only helps to reduce electron heating and keeps the acceleration much more uniform and for a longer time. However, instabilities still exist in the accelerated plasmas. Although under the perfect matching condition proton numbers can be increased by increasing the laser focus as figure 6(d) suggests, surface instability will develop after some time and destroy the acceleration structure, which limits the final proton energy [30, 31]. Suppression of such kinds of instabilities should be an important task both for the laser ion acceleration itself and for the fast ignition of inertial fusion targets based on laser-accelerated ion beams [8]. Periodic modulation may suppress or excite the instabilities. However, in our present simulation we have not observed the roughness effect on transverse instability. A detailed discussion of the surface modulation effect on acceleration stability is beyond the current topic and will be addressed in future work.

In summary, by multi-dimensional PIC simulations, we have checked the target shape effects on GeV mono-energetic proton beam acceleration. We propose using a shaped target to match laser intensity. With this, there will be a transparency region separating the acceleration region and deformation region and keeping the acceleration structure for a longer time compared with the usual flat target. The final spectrum shows a clear mono-energetic peak once the well-shaped target is used. The effects of shape factors and target surface roughness are also checked, which demonstrates the robustness of our scheme.

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