Generation of tens of GeV quasi-monoenergetic proton beams from a moving double layer formed by ultraintense lasers at intensity $10^{21}–10^{23} \text{ W cm}^{-2}$

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Abstract. We present a scheme for proton acceleration from a moving double layer formed by an ultraintense circularly polarized laser pulse with intensity $10^{21}–10^{23} \text{ W cm}^{-2}$ irradiated on a combination target. The target is composed of a thin overdense proton-rich foil located at the front followed by an underdense gas region behind with an effective $Z/A$ ratio of the order of $1/3$. When the areal density of the thin foil is small enough, the protons together with electrons in the thin overdense foil can be pre-accelerated under the laser irradiation. As the laser pulse passes through the thin foil and propagates in the underdense gas region, it excites high-amplitude electrostatic fields moving at a high speed, which appear like a moving double layer. The pre-accelerated protons can get trapped and accelerated in the moving double layer and tens of GeV quasi-monoenergetic proton beams are achieved, provided the laser intensity and plasma density are properly chosen, as demonstrated by one-dimensional (1D) and 2D particle-in-cell (PIC) simulations.

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Recently, there has been considerable interest in laser-plasma-based ion acceleration, not only for its prospect as a future compact accelerator, but also for its various potential applications, such as in the subjects of inertial confinement fusion [1], proton cancer therapy [2], radiographing transient processes [3], laser nuclear physics [4], etc. In intense laser interaction with solid targets, a few ion acceleration mechanisms have been proposed, including target normal sheath acceleration (TNSA) [5]–[10], collisionless electrostatic shock acceleration (CESA) [11]–[14], direct radiation pressure acceleration (RPA) using either linearly or circularly polarized (CP) light [15]–[25], etc. In the TNSA regime, the hot electrons produced at the front surface of the target go through the target and generate a huge electrostatic field at the rear surface of the target, which first ionizes the target at the rear surface and then accelerates the ions to energies in the several tens of MeV range. Usually the produced protons or ions have broad energy spreads in the spectra. By the use of double thin-solid targets, quasi-monoenergetic proton beams can be realized [9, 10]. On the other hand, shock wave acceleration has attracted much attention because the accelerated ions have ideally monoenergetic energy spectra. In this regime, a collisionless electrostatic shock is generated in the target and some ions in front of the shock can be reflected/trapped and get accelerated to twice the shock velocity. Unlike the accelerated ions from the rear surface in the TNSA regime, the accelerated ions here are from the interior of the target [13]. Usually the ion energy from CESA is limited to a few MeV due to the low shock speed. In the TNSA and CESA regimes, the targets are usually thick. As the target thickness is decreased, the target tends to be transparent due to the relativistic-induced transparency, and the resulting ion acceleration becomes very efficient [26]. Actually in the RPA dominant regime, the targets are usually very thin and are almost transparent [15, 16].

Most recently, a number of theoretical studies have focused on the RPA mechanism by the use of a CP laser pulse [17]–[25]. Because the ponderomotive force has no oscillating component for a CP laser pulse, the electrons are first pushed by the steady ponderomotive force and form a compressed charge layer, inducing a strong charge-separation field due to the ions left behind. This electrostatic-force pressure is balanced by the radiation pressure. Then the ions can be accelerated by the electrostatic field to very high energies with very high conversion efficiencies and very small energy spreads. Usually with this scheme the proton energy can reach the GeV level at a laser intensity around $10^{22}$ W cm$^{-2}$.

The key issue with the RPA is the formation of a stable double-layer structure moving with a high speed [24, 25]. It is well known that a laser wakefield can be regarded as a
Figure 1. The initial density distributions of the protons and heavy ions. The uniform proton density is \( n_p = 15n_c \) with a thickness of 1 \( \mu \)m (black solid line) and the heavy ion density is \( n_i = 0.1n_c \) with a length of 800 \( \mu \)m (red dashed line). The inset shows a closeup near the overdense foil.

multi-double-layer structure moving at a high speed. If some protons can be trapped, they can be accelerated like electrons [27, 28]. Actually, ion acceleration in the plasma wakefield has been proposed recently [29]–[31]. It was found that when the plasma is a mixture of protons and mainly heavy background ions, a laser pulse with an ultrarelativistic intensity can excite an ultraintense electrostatic field, in which some protons can be trapped and accelerated over a long distance to very high energies.

In this paper, we propose a new scheme for proton acceleration with the combination of RPA and laser wakefield acceleration using an ultraintense CP laser pulse with intensity \( 10^{21}–10^{23} \) W cm\(^{-2}\). This scheme is realized with a target consisting of a thin overdense proton-rich foil followed by a low-density gas region behind with an effective \( Z/A \) ratio of the order of 1/3. It was found that the protons in the overdense layer are first accelerated via the laser pulse to the GeV level by the phase stable acceleration [18, 22], a kind of RPA. When they are injected into the underdense gas region, they can be trapped by a strong wakefield driven by the laser pulse. The protons are accelerated continuously until either the laser energy is depleted in the underdense plasma or the protons have overtaken the laser pulse. The proposed scheme has been verified both by one-dimensional (1D) and 2D particle-in-cell (PIC) simulations with the codes KLAP [32] and LAPINE developed by our group.

2. PIC simulation results

2.1. 1D PIC simulations

As shown in figure 1, the proposed target is composed of an overdense plasma layer and a tenuous long plasma layer. The ions in the overdense layer are purely protons for simplicity and the ions in the tenuous plasma layer are heavy ions with an effective \( Z/A \) ratio of the order of 1/3 to distinguish them from the protons. The density \( (n_0) \) and thickness \( (L) \) of the overdense
proton plasma layer should be set by \( n_0L \sim a_0n_i\lambda_0/2\pi \). Here, \( a_0 \) is the normalized peak laser amplitude, which is related to the laser intensity by \( I\lambda_0^2/a_0^2 = 2.74 \times 10^{18} \text{ W cm}^{-2} \mu \text{m}^{-2} \) for CP light, \( n_c = \omega^2m_e/4\pi e^2 \) is the critical density for the corresponding incident laser wavelength \( \lambda_0 \), with \( m_e, e \) and \( \omega \) being the mass and charge of the electron and the frequency of the incident laser pulse, respectively. In the following, we take the proton foil density of \( n_p = 15n_c \) with a thickness of \( 1\lambda_0 \) to avoid the numerical problem with too much difference between the plasma densities in the overdense foil and the tenuous plasma layer. In the real situation, one can take the solid density with reduced target thickness while keeping the areal density \( n_0L \). Alternatively, one can produce a low-density foil by prepulse irradiation onto a solid foil [33]. For the tenuous plasma part, the heavy ions have a density of \( n_i = 0.1n_c \) with a length of \( 800\lambda_0 \). Here we take a relatively high underdense plasma density to limit the propagating speed of the laser light, which enables proton trapping to occur more easily when the pre-accelerated protons are injected. A CP laser pulse that propagates along the \( z \)-direction reaches the left boundary of the target at \( t = 0 \). It has the temporal profile \( a = a_0\sin^2(\pi t/t_L) \) with \( 0 \leq t \leq t_L \), where \( a_0 = 200 \) is a normalized peak amplitude corresponding to a laser intensity of \( 1.1 \times 10^{23} \text{ W cm}^{-2} \) for \( \lambda_0 = 1 \mu \text{m} \), and \( t_L = 25\tau \) is the duration of the laser pulse with \( \tau = 2\pi/\omega \) being a laser cycle.

Figure 2 shows snapshots of the laser pulse, the electron density, the proton density and the heavy ion density as well as the longitudinal electrostatic field at different times. For a CP laser pulse, there is no oscillating component in the ponderomotive force, so that the electron dynamics is dominated by the laser pulse profile. As shown in figures 2(a) and (b), at the beginning of the laser pulse interaction with the target, the electrons are first pushed by the steady laser ponderomotive force and quickly piled up in a compressed layer in front of the laser pulse, inducing a strong charge-separation field behind. Behind the laser front, some proton density spikes are found. They are accelerated from the thin foil by the induced large electric field. At \( t = 50\tau \), the maximum proton velocity is \( v_{p,\text{max}} = 0.9316c \), still lower than the average phase velocity of the electrostatic field \( v_\beta \approx 0.9840c \) by measuring the position of the peak electrostatic field at \( t = 50\tau \) and \( t = 800\tau \). But they are high enough to be trapped and get further accelerated in the underdense plasma region. The protons are accelerated very quickly, at \( t = 100\tau \), some energetic protons accelerating with the maximum velocity \( v_{p,\text{max}} = 0.9814c \). The electrostatic field running with the laser pulse shows a well-formed double-layer structure and can keep high amplitudes during the whole accelerated regime. As shown in figure 2(d), it is found that the normalized peak intensity of the electrostatic field is \( E_{z,\text{max}} = 39.83(m_eoc/e) \), corresponding to an accelerating gradient of \( 128 \text{ GeV mm}^{-1} \), and the proton beam is indeed trapped and accelerated in the electrostatic field at \( t = 400\tau \). In addition, we can find that around the turning point of the double layer, some heavy ion density spikes are formed. The heavy ions behind the laser pulses are also accelerated to quite a high energy in the positive field region of the double layer; however, they cannot be trapped in the electrostatic field, since the maximum velocity of the tritium ions is \( 0.5746c \) at \( t = 400\tau \), which is much lower than the phase velocity of the electrostatic field. Also we can find that laser pulse front erosion occurs strongly as shown in figures 2(c) and (e); this was first observed by Decker et al [34]. This is because the laser pulse front is depleted by driving the huge electrostatic field structure as well as electron acceleration in the underdense plasma. At \( t = 800\tau \), the proton beam front has pulled up to the compressed electron layer at the laser front and is about to run out of the electrostatic field.

\[ \text{Numerical simulation with the 1D Lagrangian fluid code MEDUSA shows that, when a real thin-solid target with a thickness of } 0.1\lambda_0 \text{ is irradiated by a picosecond laser at } 10^{14} \text{ W cm}^{-2}, \text{ it expands in 10 ps to around } \lambda_0 \text{ with the peak density around } 20n_c. \]

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Figure 2. Snapshots of the laser pulse $E_x e/m_e c^2$ ((a), (c) and (e)), the electron density $n_e/n_c$ (black solid line), the proton density $n_p/n_c$ (red solid line) and the heavy ion density $n_i/n_c$ (green solid line) as well as the longitudinal electrostatic field $E_z e/m_e c^2$ (blue dashed line) ((b), (d) and (f)) at different times. The initial plasma parameters are given in figure 1 and the laser pulse is circularly polarized with a temporal profile $a = a_0 \sin^2(\pi t/t_L)$ with $0 \leq t \leq t_L$, where the peak normalized amplitude $a_0 = 200$ and the duration $t_L = 25 \tau$ with $\tau = 2\pi/\omega$ being a laser cycle.

with a maximum energy of about 63 GeV, as shown in figure 2(f), indicating that the wakefield acceleration process is about to finish. The corresponding average accelerating gradient is about 79 GeV mm$^{-1}$. Finally, we can find that about 9.5% of the protons from the thin foil are trapped and accelerated, corresponding to about 20 nC for a beam diameter of 10 µm, with the maximum energy of about 63.18 GeV and the full-width at half-maximum (FWHM) energy spread <2% at $t = 850\tau$, as shown in figures 3(a) and (b) for the longitudinal phase space distribution and the energy spectrum of the proton beam, respectively.

Figure 4(a) shows a comparison of the maximum energies of the accelerated protons achieved with time for the two cases, with or without the underdense gas region behind the proton foil. It is shown clearly that at the very beginning of the interaction of the laser pulse with the targets, the maximum energies of protons are very close to each other in the two cases. As shown in figure 4(a), the maximum energies of protons are 0.601 GeV for the target with underdense gases and 0.579 GeV for the target without underdense gases at $t = 20\tau$, and they increase to 1.646 and 0.943 GeV, respectively, at $t = 50\tau$. However, above $t = 50\tau$, the maximum energies of protons are continually and dramatically increased if there are underdense gases behind the proton foil, since the protons can get trapped and be accelerated in the wakefield. In this case, as shown in figure 4(b), the high-amplitude longitudinal electrostatic fields are excited in the underdense plasma, and retain good waveforms with time with an average field strength at the peak $E_{z,\text{max}} \sim 28.92 m_e c^2/e$. From this average field
Figure 3. The longitudinal phase space for momenta $p_z/m_c$ (a) and the energy spectrum of the trapped protons (b) at $t = 850\tau$. The parameters for the plasma and laser pulse are the same as those given in figure 2.

strength, we can estimate the maximum energy that the protons achieved in the wakefield $W_{\text{max}} = e\bar{E}_z,\text{max}l_{\text{acc}} \sim 69.6\text{ GeV}$ at $t = 800\tau$ accounting for an accelerating distance of about 0.75 mm [28], which is quite close to the simulation result.

In order to verify that protons gain energy mainly from the wakefield acceleration rather than from the direct laser acceleration in the underdense plasma region, we can use the relation $\gamma - 1 = \Gamma_\parallel + \Gamma_\perp$ [35]. Here $\gamma - 1$ stands for the total energy gain, $\Gamma_\parallel = \int_0^t E_z v_z \, dt'$ represents the energy gain from the longitudinal electrostatic field, and $\Gamma_\perp = \int_0^t E_\perp v_\perp \, dt'$ stands for the energy gain from the direct laser acceleration with the normalized transverse field $E_\perp$. Figure 5 shows the distributions of the protons in $\Gamma_\parallel \sim \Gamma_\perp$ space at $t = 50\tau$ and $t = 800\tau$. It is clearly seen that the protons gain energy mainly from the longitudinal electrostatic field rather than from the transverse laser field in both cases. In fact, direct coupling of the laser energy to the protons cannot happen below the proton relativistic threshold intensity $\sim 10^{24}\text{ W cm}^{-2}$ [30]. Note that the
Figure 5. Proton energy gain from the longitudinal electrostatic field $\Gamma_{\parallel}$ versus that from the transverse laser field $\Gamma_{\perp}$ at $t = 50\tau$ (a) and $t = 800\tau$ (b). The parameters for the plasma and laser pulse are the same as those given in figure 2.

Figure 6. Maximum energies of the accelerated protons with time for different durations of the laser pulses (a) and for different ion densities in the underdense region (b). Other parameters are the same as those given in figure 2.

proton energy is weakly modulated by the transverse laser field. This is in contrast with electron acceleration in the laser wakefield, where the laser field can affect the electron acceleration in the first period of the wakefield more obviously even at an intensity of $10^{18}$ W cm$^{-2}$ [36].

For the described scenario of proton acceleration, there are many parameters that may change the results. The laser intensity is one of the key parameters, which will be addressed in detail in section 3. Here we just show the effects of the laser pulse duration and the underdense plasma density. Figure 6(a) shows the maximum energies of the accelerated protons with time for different durations of the laser pulse $t_L$. It is found that the optimal laser pulse duration is around $t_L = 25\tau$. If the laser pulse is too short, such as $t_L = 15\tau$, the laser pulse is almost completely depleted around $t = 600\tau$. Once the laser pulse is completely depleted, the wakefield immediately decays, which leads to a shorter acceleration length and lower proton energies than the case of $t_L = 25\tau$. On the other hand, if the laser pulse is too long, such as $t_L = 50\tau$, the laser pulse cannot well transmit through the foil. As a result, the main acceleration is more like RPA instead of wakefield acceleration. It is clearly found that the acceleration gradient
of RPA is much smaller than that of wakefield acceleration. Figure 6(b) shows the maximum energies of the protons with time for different underdense plasma densities. We found that the higher the underdense plasma density, the lower the maximum proton energy that is achieved. This is because the etching velocity of the laser pulse front is 
\[ v_{\text{etch}} = \frac{\omega_p^2}{\omega^2} \]
with \( \omega_p \) being the underdense plasma frequency [34], which indicates that the higher the underdense plasma density, the shorter the time it takes to completely deplete the laser energy. As a result, the final maximum proton energy becomes lower with increasing underdense plasma density. However, we found that the acceleration gradient becomes larger before reaching energy saturation with increasing underdense plasma density because the laser energy converts into wakefield energy more quickly. On the other hand, if the plasma density is too low, the phase velocity of the wakefield would be so large that the proton trapping process cannot occur. This implies that there is an optimal underdense plasma density.

2.2. 2D PIC simulations

2D PIC simulation results indicate that the acceleration mechanisms are also effective. The incident CP laser pulse with a normalized peak amplitude \( a_0 = 200 \), a pulse duration of \( 20\tau \), a spot size \( R_0 = 8\, \mu m \) and a wavelength of \( 1\, \mu m \) reaches the left boundary of the plasma target at \( t = 0 \). The proton foil has a density of \( n_p = 50n_c \) with a thickness of \( 1\, \mu m \). Instead of using a simple plane foil, we adopt the target with a finite transverse dimension less than the laser spot size, say \( 4\, \mu m \), in our simulation. This is to avoid the transverse spreading of accelerated protons due to the space charge effect at the earlier stage. Behind the overdense target is the underdense gas with an effective \( Z/A \) ratio of the order of \( 1/3 \), which has a density of \( n_i = 0.2n_c \) with a length of \( 800\, \mu m \). Again, the underdense gas density is taken to be relatively high to limit the propagating speed of the laser light, which enables proton trapping to occur more easily. The number of grid cells and cell dimensions are \( 2400 \times 1200 \) and \( 0.025 \times 0.08 \), with 225 and 16 particles per cell in the proton region and underdense gas region, respectively, i.e. different particle weights are adopted for the low- and high-density regions. The simulation is done with our code LAPINE using the moving window technique.

Figure 7 shows snapshots of the laser energy, the excited longitudinal electrostatic field and the proton density, as well as their distributions on the optical axis at \( t = 40\tau \) and \( t = 800\tau \). At first, the longitudinal ponderomotive force pushes the electrons forward, exciting a strong longitudinal electrostatic field \( E_z \) (normalized by \( m_e\omega c/e \)). This field pre-accelerates the protons in the overdense foil target at the beginning of the laser interaction with the plasma target, as shown in figures 7(b) and (d). Note that the laser pulse front shows a wing structure in figure 7(a). The corresponding transverse ponderomotive force helps us to reduce the transverse spreading of the proton beams caused by the space charge fields. Later, when the laser pulse propagates in the underdense gas, the longitudinal electrostatic field that shows a double-layer structure becomes even larger, as shown in figures 7(b) and (f). This longitudinal electrostatic force is the dominant acceleration force as the laser pulse front gradually spreads after \( t = 200\tau \). At \( t = 800\tau \), the laser pulse front has fully branched off and the laser energy on the optical axis is almost zero, as shown in figures 7(e) and (h). On the other hand, the pre-accelerated protons get trapped into the electrostatic field and are further accelerated to very high energies. As shown in figure 7(h), at \( t = 800\tau \), the proton beam has run out of the electrostatic field, indicating that the acceleration process has almost finished. Comparing the density distributions of the protons on the optical axis in figures 7(d) and (h), we found that the proton beam still has a high
density, although it has been propagating over a long distance and gradually defocused by the transverse electrostatic field due to the space charge effect. Thanks to the smaller transverse dimension of the proton target with a radius less than the laser spot size, the high-density proton layer can be wrapped around and guided by the oversized rim of the laser spot, with ponderomotive force confinement [37]. It is found that the forked laser pulse causes a large number of electrons to remain near the optical axis, greatly reducing the Coulomb explosion effects of the protons.

Figure 8 shows the energy distribution in the phase space, as well as the energy spectrum of the trapped protons at $t = 800\tau$. We found that the protons in the front of the beam have decelerated, indicating the acceleration has almost finished, as shown in figure 8(a). Also we found that a quasi-monoenergetic proton beam with a maximum energy equal to about 26 GeV and an FWHM energy spread $<10\%$ is achieved, as shown in figure 8(b). This energy spectrum is better than that of the nearly 100% energy spread via the pure wakefield proton acceleration.
Figure 8. Energy distribution in the phase space (a), as well as the energy spectrum of the trapped protons (b) at $t = 800\tau$. The parameters for the plasma and laser pulse are the same as those given in figure 7.

mechanism with a more intense laser pulse [31]. Also, with the present scheme, trapped quasi-monoenergetic protons can be much larger, for example exceeding $10^{11}$.

3. Acceleration in the laser intensity range of $10^{21} – 10^{23}$ W cm$^{-2}$

According to a series of 1D PIC simulations, we found that the scheme with a combination of RPA and laser wakefield acceleration works only when two conditions are satisfied: one is that the proton in the high-density foil can be pre-accelerated to the GeV level in the RPA regime; another is that the laser pulse can obviously transmit the overdense foil to generate wakefields in the underdense plasma. These conditions may be satisfied in quite a broad laser intensity range with target parameters adjusted correspondingly. Actually, it is found that when the normalized peak amplitude of the laser pulse $a_0$ varies from 50 to 250, corresponding to intensities from $6.85 \times 10^{21}$ to $1.71 \times 10^{23}$ W cm$^{-2}$, the acceleration mechanism can be made quite effective by choosing proper laser and plasma parameters.

As shown in figure 9(a), within $150 \leq a_0 \leq 250$ and with the pulse duration of $t_L = 25\tau$ while keeping target parameters the same as those given in figure 2, the protons can be accelerated to the GeV level in the RPA regime for the pure proton foil at $t = 50\tau$. Meanwhile, in this laser intensity range, the laser pulse can obviously transmit through the foil to generate a large wakefield in the underdense plasma. So the pre-accelerated protons can be trapped and accelerated in the wakefield. It is found that the average peak wakefield increases with the laser intensity, resulting in an increase of the maximum energy of the trapped protons, as shown in figures 9(b) and (c). Note that the proton energy appears to scale approximately with the incident laser amplitude $a_0$, which is similar to that mentioned in [31]. This agrees qualitatively with the scaling for the wakefield acceleration. According to the wakefield acceleration [28, 38], the
The maximum energies that the pre-accelerated protons achieved with the normalized peak amplitude of the laser pulse $a_0$ for the pure proton foil at $t = 50\tau$; (b) the average peak longitudinal electrostatic field $\bar{E}_{z,max}e/m_oe\omega_c$ with different $a_0$; (c) the maximum energies of the trapped proton with different $a_0$; and (d) the energy spectra with different $a_0$. The duration of the laser pulse is $t_L = 25\tau$ and the plasma parameters are the same as those given in figure 2.

The maximum relativistic factor for protons is given by

$$\gamma_{\max} = \gamma_\beta^2 \left( \Delta\phi_{\max} + \gamma_\beta^{-1} + \beta \sqrt{\Delta\phi_{\max}^2 + 2\gamma_\beta^{-1}\Delta\phi_{\max}} \right),$$

where $\beta$ is the phase velocity of the wakefield or the group velocity of the laser pulse in underdense plasma, $\gamma_\beta = (1 - \beta^2)^{-1/2} \approx \omega_0^{1/2}/\omega_p \sim \omega_0 a_0^{1/2}/\omega_p$ because of $\gamma_0 \approx (1 + a_0^2)^{1/2}$, and $\Delta\phi_{\max}$ is the maximum scalar potential of the wakefield normalized by $m_pc^2$. If $\beta \sim 1$ and $a_0 \gg 1$, $\gamma_{\max} \approx 2\gamma_\beta^2\Delta\phi_{\max}$. From figure 9(b), $\Delta\phi_{\max} \sim a_0^{1/4-1/2}$. Therefore $\gamma_{\max} \propto a_0^{5/4-3/2}$. On the other hand, because $a_0$ changes with time considerably, the scaling of $\gamma_\beta$ with $a_0$ can be less $\propto a_0^{1/2}$. Therefore the index for the power law scaling of $\gamma_{\max}$ with $a_0$ can be reduced to close to 1. Figure 9(d) shows four typical energy spectra for different $a_0$, where quasi-monoenergetic proton beams with maximum energies of a few tens of GeV are achieved.

For $a_0 < 150$, the laser pulse cannot obviously transmit through the foil at the same target parameters, so that the laser wakefield acceleration does not work any more under such parameters. In such cases, thin overdense targets shall be adopted. For example, we found that within $80 \leq a_0 \leq 120$, a thinner proton foil with a length of $L = \lambda_0/2$ and a longer laser pulse with a duration of $t_L = 50\tau$ should be used in order to satisfy the two conditions mentioned above. For instance, when $a_0 = 100$, the pre-accelerated proton energy is 1.48 GeV at $t = 50\tau$ via RPA, corresponding to a velocity of 0.9218c, which is high enough to be trapped in the

**Figure 9.** (a) The maximum energies that the pre-accelerated protons achieved with the normalized peak amplitude of the laser pulse $a_0$ for the pure proton foil at $t = 50\tau$; (b) the average peak longitudinal electrostatic field $\bar{E}_{z,max}e/m_oe\omega_c$ with different $a_0$; (c) the maximum energies of the trapped proton with different $a_0$; and (d) the energy spectra with different $a_0$. The duration of the laser pulse is $t_L = 25\tau$ and the plasma parameters are the same as those given in figure 2.

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Figure 10. Energy spectra of the trapped protons for different \(a_0\) at \(t = 850\tau\) when the thickness of the high-density proton foil \(L = \lambda_0/2\) (a) and \(L = \lambda_0/3\) (c). Comparison of the maximum energies the accelerated protons achieved with time for the two cases with or without the underdense plasma region behind the proton foil for \(a_0 = 100\), \(L = \lambda_0/2\) (b) and \(a_0 = 50\), \(L = \lambda_0/3\) (d). The duration of the laser pulse is \(t_L = 50\tau\) and other parameters are the same as those given in figure 2.

wakefield and get accelerated over a long distance. At \(t = 750\tau\), the wakefield acceleration is about to finish. The energy spectrum of the trapped protons is shown in figure 10(a) and we find that the maximum energy is about 28 GeV and the FWHM energy spread of the main spike is \(<3\%\) at \(t = 850\tau\).

If the laser intensity is even lower, such as within \(50 \leq a_0 \leq 70\), an even thinner proton foil such as with a length of \(L = \lambda_0/3\) should be used. It was found that quasi-monoenergetic proton beams with maximum energies of tens of GeV can also be achieved via the combination acceleration mechanism, as shown in figure 10(c). It was also found that although the RPA mechanism is quite effective under the same laser conditions, the combination acceleration still has a larger acceleration gradient and the maximum proton energy is much higher than the one in the pure RPA regime, as shown in figures 10(b) and (d). In addition, the phenomenon of the higher the underdense plasma density the lower the maximum proton energy achieved due to the quicker laser energy depletion also occurs at low laser intensities, similar to those shown in figure 6(b).

4. Summary

In summary, we have presented an effective scheme for proton acceleration by irradiation of a thin high-density proton foil followed by a low-density underdense gas with an effective \(Z/A\)
ratio of the order of 1/3 by an ultraintense CP laser pulse via 1D and 2D PIC simulations. Both 1D and 2D simulation results show that the electrons are first pushed forward by the steady ponderomotive force and form a compressed charge layer in front of the laser pulse, exciting a strong electrostatic field, which pre-accelerates protons. When the laser pulse is transmitted through the proton foil and propagates in the underdense gas target, a strong wakefield is produced, which appears like a double layer moving at a phase velocity equal to the group velocity of the laser pulse. By controlling the areal density of the thin proton foil and the intensity and duration of the incident laser pulse, as well as the underdense plasma density, the pre-accelerated protons can be trapped in the positive field region and accelerated over a long distance to very high energies. Simulations demonstrate that this mechanism can work in a wide laser intensity range such as $10^{21} - 10^{23}$ W cm$^{-2}$.

We note that the accelerated proton beams found in the present scheme are located in a very narrow space region, leading to strong space charge effects, in particular in the multi-dimensional geometry. To avoid this, one may introduce a thin foil with finite transverse size less than the laser spot size because the oversized rim of the laser spot can wrap around the high-density proton beam with ponderomotive force confinement and allows for collimated acceleration.

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