Proton acceleration in underdense plasma by ultraintense Laguerre–Gaussian laser pulse

Xiaomei Zhang, Baifei Shen, Lingang Zhang, Jiancai Xu, Xiaofeng Wang, Wenheng Wang, Longqiong Yi and Yin Shi
State Key Laboratory of High Field Laser Physics, Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201800, People’s Republic of China
E-mail: zhxm@siom.ac.cn and bfshen@mail.shcnc.ac.cn

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Abstract
A three-dimensional (3D) particle-in-cell (PIC) simulation is used to investigate witness proton acceleration in underdense plasma with a short intense Laguerre–Gaussian (LG) laser pulse. Driven by the LG₁₀ laser pulse, a special bubble with an electron pillar on the axis is formed in which protons can be well confined by the generated transversal focusing field and accelerated by the longitudinal wakefield. The risk of scattering prior to acceleration with a Gaussian laser pulse in underdense plasma is avoided, and protons are accelerated stably to much higher energy. In the simulation, a proton beam has been accelerated to 7 GeV from 1 GeV in underdense tritium plasma driven by a 2.14 × 10²² W cm⁻² LG₁₀ laser pulse.

Keywords: proton acceleration, Laguerre–Gaussian laser pulse, bubble

1. Introduction

Proton acceleration by the intense circularly polarized (CP) laser pulse (which often is \( I \sim 10^{22} \text{ W cm}^{-2} \)) in a radiation pressure acceleration (RPA) regime has recently become the focus of research [1–13]. Simulations and theoretical analyses have shown that a high-quality proton beam with Gigaelectron volts (GeV, \( 10^9 \text{ eV} \)) can be generated from the interaction between a short laser pulse and a thin foil [2, 4, 9–11, 14]. Considering its huge potential...
applications, some promising works are in progress. Increasing the energy of accelerated protons by RPA is difficult because of the decreasing acceleration gradient after the accelerated proton velocity approaches light speed. In addition, many undesirable effects, such as multidimensional instabilities [15–17], occur during acceleration with a long interaction time even if the laser pulse can be well controlled. Therefore, protons of energy beyond 5 GeV are rather hard to obtain through the RPA mechanism.

On the other hand, tens of GeV or even a TeV high-quality proton beam can be generated in the so-called sequential radiation pressure and bubble acceleration regime [18–22] using a $10^{23} \text{W cm}^{-2}$ laser pulse with two-dimensional (2D) PIC simulations. The plasma channel can help to form the twin bubble structure; thus, the proton energy can be over 10 GeV [22]. This promising approach can compete with the conventional accelerator in obtaining the ultra-high energy protons when laser technology meets the requirement in the near future, and the same encouraging results as the electron acceleration in the bubble are expected for protons. So, it is necessary to study the detailed process.

We know that to get high energy protons there are two key stages, namely trapping and continual acceleration. The former can be reached by RPA such as in the sequential radiation pressure and bubble acceleration regime. It has been found that a quasi-monoenergetic plasma bunch of high energy density can be obtained by irradiating a currently available short laser pulse irradiating on a small hemispheric shell target [23], which can also be used in the trapping process in the bubble. For obtaining ion energy higher than 5 GeV, the second stage, continuous acceleration, is more critical and challenging. In the regular bubble, electrons can be well confined on the acceleration axis because of the transverse focusing field and can be continuously accelerated in the laser propagation direction. However, for protons, it is the opposite situation: protons will be dispersed by the radial electric field and will thus be difficult to further accelerate without an additional compensation method. We note the recent work, which has reported special donut wakefields driven by a LG laser pulse for positron and electron acceleration [24]. For positron acceleration, the laser pulse should be short enough to avoid affecting the positron because the acceleration and the laser fields coexist in the same space. However, the proton mass is much larger; so, it may be more appropriate to use such a donut wakefield to accelerate protons because of the limited effect of the laser field on them.

In this paper, the well-confined acceleration of externally injected protons in the wakefield driven by a LG laser pulse is studied using 3D PIC simulations. The trapping conditions and acceleration results are analyzed. It is found that, different from the regular bubble induced by a Gaussian laser pulse, a special bubble with an electron pillar on the axis will be formed when a LG laser pulse irradiates in underdense plasma. This structure provides an efficient and strong focusing force for protons in the transverse direction; thus, protons can be accelerated continuously for a long time. The 3D PIC simulations confirm that a proton beam with an initial energy of 1 GeV was accelerated to 7 GeV in the underdense plasma with a density of $2.4 \times 10^{20} \text{cm}^{-3}$. This acceleration is stimulated using a LG_{10} laser pulse with power similar to the Super–Gaussian (SG) laser pulse with an intensity of $2.14 \times 10^{22} \text{W cm}^{-2}$.

2. Simulation and analysis

The proposed method is demonstrated with a 3D PIC simulation code (VORPAL) [25]. The simulation box is $60 \mu \text{m}(x) \times 100 \mu \text{m}(y) \times 100 \mu \text{m}(z)$, which corresponds to a moving
window with 600 × 300 × 300 cells and one particle per cell. The tritium underdense plasma occupies the 12 μm < x < 1000 μm region in the propagation direction of the laser pulse, and −35 μm < y(z) < 35 μm, with a density of n₀ = 2.4 × 10²⁰ cm⁻³. Here, the slow-moving massive background tritium ions allow the formation of a stable electron bubble with a large space-charge field [26]. Actually, there is no evident difference if other heavy-ion plasmas or proton plasmas are used. The used CP LG₁₀ laser pulse is described as

\[ a = a₀ \left( \sqrt{2} r/l₀ \right) \exp \left( -r^4/l₀^4 \right) \exp (iφ) \sin^2 \left( \pi t/(2t₀) \right) \]

with \( n₀ = 7 \) μm and \( t₀ = 12.5 T \), where \( T \) is the laser period, and \( φ \) is the azimuthal angle within the range of [0 2π]. The laser electric field is used with power similar to that of the SG laser pulse with a peak intensity of 2.14 × 10²² W cm⁻², which corresponds to its normalized amplitude \( a₀ = eA/m_e c^2 = 70.7 \) for the laser pulse with wavelength \( λ = 0.8 \) μm, where \( A \) is the vector potential, \( c \) is the light speed in vacuum, \( m_e \) is the electron mass and \( e \) is the electron charge. At \( t=0 \), the laser pulse enters the simulation box from the left boundary. The witness proton beam emitted from \( x = 5 \) μm, \( y = z = 0 \) μm is of the size of \( 3 \) μm × \( 1 \) μm × \( 1 \) μm with a total charge of 160 pC.

The background electrons are expelled by an intense laser pulse through the pondermotive force, which is proportional to \( VI \). In a regular bubble driven by a Gaussian laser pulse, the transverse field will disperse protons located near the x-axis and push them to the bubble sheath wall. However, in the case of a LG laser pulse, the LG₁₀ laser pulse has a hollow-structure electric field, as shown in figure 1, in which the field on the axis is zero. Therefore, electrons expelled outward by the pondermotive force of the laser pulse in a transversal direction form the outer bubble sheath, whereas the electrons expelled inward form the inner bubble sheath. That is, a bubble structure with an electron pillar on the x-axis will be formed when it propagates in the underdense plasma because of its transverse donut-like shaped intensity [24, 27]. The electron pillar on the x-axis of the special bubble structure will result in a focusing field for protons around the inner electron pillar. If the transverse laser ponderomotive force is sufficiently intense to compress the inner electron pillar to an electron thread with high density, the wakefield can trap and accelerate protons for a long time. In this case, this structure provides the focusing force for protons in the transverse direction and for the accelerating force in the

**Figure 1.** Field distributions of the LG₁₀ laser pulse at \( t = 160 \) fs are given (a) in the x-y plane at \( z = 0 \) and (b) in the y-z plane at \( x = 39 \) μm. The field is normalized to \( m_e \omega₀ e_0 \), where \( ω₀ \) is the laser frequency.
longitudinal direction. With the parameters in this paper, a clear special bubble structure with a high density electron thread is formed, as shown in figure 2. The charge density of the electron thread is higher than the background ion density. Also, there is a high density electron bunch in the rear of the special bubble. Actually, the high density electron bunch in the rear of the special bubble in figure 2(a) is not trapped in the present simulation and is unstable. At the later time, there is no obvious electron density peak in the rear of the bubble, and it does not influence the proton acceleration. Therefore, it will not be described specifically.

The electric fields at $t = 1.12$ ps in the longitudinal and transverse directions in the special bubble are shown in figure 3 from the 2D simulation with constant physical parameters in order to observe the fields clearly. The longitudinal wakefield around the $x$-axis is about $6m_e\omega_0c/e$, which can accelerate protons. More importantly, there is indeed a transverse focusing field, as shown in figure 3(b), which is expressed by $\sim(E_y - cB_z)$. Simultaneously, the witness proton beam is located in the black-dashed box and is confined by the focusing field. The focusing field
is similar to the twin bubbles in the previous study [22] but with different generation schemes. In the present study, the structure has axial symmetry, which is decided by the laser pulse mode and can propagate stably for a long distance for proton acceleration. As expected, protons are well confined transversely on the axis in the special bubble driven by the LG10 laser pulse, shown in figure 4(a), with the momentum distribution at $t=1.12$ ps (most protons are located in a bucket within the radius of $r=1 \mu m$ in the transverse direction), and accelerated stably to $t=2.13$ ps when they start dephasing (surpassing the bubble front). Eventually, the witness protons gain the peak energy of 7 GeV, as shown in figure 4(b). In the case of a SG laser pulse, which keeps other simulation parameters unchanged, the protons diffuse gradually and cannot be accelerated stably. Figure 4(c) shows the proton beam filling with the simulation box (out of the bubble). Finally, the peak energy stops at 2.2 GeV.

3. Discussion

There are two important aspects for the present acceleration approach. First, we should note that the electron pillar in the special bubble structure, which determines the longitudinal acceleration
field for the witness proton beam, is crucial for the acceleration. If the electron pillar is too thick, the wakefield around the witness protons will be too weak to accelerate the protons because the charge separation field is almost neutralized. Therefore, the laser intensity, laser spot size and plasma density should be adjusted to be appropriate to make the inner electron pillar thin enough to make the longitudinal acceleration field intense enough. Assuming the bubble is spherical-like, its radius (the distance between the bubble wall and the electron thread) can be estimated by balancing the transverse laser ponderomotive force on a single electron and on the transverse charge separation field force [28]. The transverse ponderomotive force of the CP laser pulse is \( F_{\text{pond}} = e^2/(4m_e\omega_0^2)VE^2 \), where \( E = m_e\omega_0c/e \). The transverse charge separation field force is \( E_{\text{trans}} = 4\pi e^2nR \), where \( R \) is the bubble radius. Then,

\[
(R/\lambda) = \left( a_0/2\pi \right) \sqrt{n_c/2n_e},
\]

where \( n_c = m_e\omega_0^2/(4\pi e^2) \) is the critical plasma density. Figure 2 shows that the radius \( R \approx 15 \mu m \) is consistent with equation (1). The radius minimally changes because of the strong non-linear effects. On the other hand, for the ultra-intense LG laser pulse, the special bubble radius is also related to the laser spot size for its shaped intensity and requires \( r_0 \approx R/2 \). This relationship is important for the formation of the special bubble, which is appropriate to accelerate protons because, in this case, the inner electron pillar can be compressed to the thin electron thread, and its thickness can be neglected. On the presence of the thin electron thread, the focusing force \( F_r = e(E_x - cB_z) \sim en_0 \) in the transverse direction is induced.

Another important aspect is the trapping and energy gain of the witness protons. The initial energy of the witness protons required for trapping depends on the potential in the special bubble (intensity of the acceleration field). The Hamiltonian of a proton in the wakefield and the electromagnetic field is \( h_0 = \sqrt{1 + p_x^2 + \rho_p^2 \alpha^2} - \rho_p \phi(\xi) - v_p P_x \), where \( \xi = x - ct \), \( h_0 \) is an integration constant corresponding to the initial proton condition in front of the bubble \( p_x = \gamma v_x \) is the proton longitudinal momentum, \( \rho_p = -1/1836 \), \( \phi(\xi) = \int E_x d\xi \) is the scalar potential, \( E_x \) is the acceleration field with the peak intensity estimated roughly using \( E_{x_{\text{max}}} \approx \sqrt{a_0} \) for the Gaussian pulse [28] and \( v_p \) is the bubble velocity related to the plasma density and the laser intensity. For the ultraintense LG laser pulse, the wakefield on the axis is slightly weaker due to the transverse-shaped intensity. For simplicity, we define the longitudinal wakefield, which increases linearly within \( 0 < \xi < R \) and decreases linearly within \( R < \xi < R + d_{\text{skin}} \) with \( E_{x_{\text{max}}} \approx \eta \sqrt{a_0} \), where the wakefield is zero at \( \xi = 0 \), and \( d_{\text{skin}} \sim 1/ \sqrt{n_e} \) is the skin width of the high density electron sheet in front of the bubble; \( \eta \leq 1 \) is a factor used to describe the estimated maximum wakefield driven by the LG laser pulse.

For the ultraintense CP laser pulse interacting with the underdense plasma, the high density electron sheet in front of the laser pulse expelled by the intense light pressure is overdense, and the laser pulse is reflected. By balancing the momentum of the electron layer with the light pressure and by considering the Doppler effect [29], \( 2I/c(1 - v_p/c)/(1 + v_p/c) = 2\rho_p^2 n_e m_e v_p^2 \), the bubble velocity can be obtained as follows
where \( n_e \) is the electron layer density, which can be obtained by \( n_e \sim n_0R/d_{\text{skin}} \). From equation (3), \( v_p = 0.96 \) agrees well with that of \( \gamma_{\text{end}} \sim (v_p \sim 0.967\gamma_p = 3.9) \) from the above simulation. The protons are accelerated from the onset of their injection into the bubble from the bubble front. Until the proton velocity becomes equal to the bubble velocity, the protons are trapped in the bubble and accelerate continually. The trapping condition can be written as follows

\[
v_p = \frac{a\sqrt{n_e/n_e}}{1 + a\sqrt{n_e/n_e}}, \tag{3}\]

where \( n_e \) is the electron layer density, which can be obtained by \( n_e \sim n_0R/d_{\text{skin}} \). From equation (3), \( v_p = 0.96 \) agrees well with that of \( \gamma_{\text{end}} \sim (v_p \sim 0.967\gamma_p = 3.9) \) from the above simulation. The protons are accelerated from the onset of their injection into the bubble from the bubble front. Until the proton velocity becomes equal to the bubble velocity, the protons are trapped in the bubble and accelerate continually. The trapping condition can be written as follows

\[
h_0 + \rho_p\phi_{\text{trap}} = 1/\gamma_p, \tag{4}\]

where \( \gamma_p = 1/\sqrt{1 - v_p^2} \) and \( \phi_{\text{trap}} \) is the potential required for trapping. For the protons injected with an initial positive velocity \( v_0 \), \( h_0 = \gamma_0(1 - v_pv_0) \), where \( \gamma_0 = 1/\sqrt{1 - v_0^2} \).

The potential required for trapping \( (\phi_{\text{trap}}) \) and the energy after the positive acceleration field \( (\gamma_{\text{end}}) \) with different initial energies \( (\gamma_0) \) of the witness proton are shown in figure 5(a) in which \( \eta = 2/3 \), according to the simulation results. With the increasing initial energy of the witness proton, the required potential decreases. The trapping of the protons depends on the maximum potential \( \phi_{\text{max}} = \int_0^{R+d_{\text{skin}}} E_x dx \). With these simulation parameters, \( \phi_{\text{max}} \approx 380 \), which correspond to the initial energy \( \gamma_{\text{0 min}} \approx 1.4 \). For protons with an initial energy lower than \( \gamma_{\text{0 min}} \), they will leave behind the acceleration phase and cannot be trapped, such as the protons at rest initially requiring the potential of \( \phi_{\text{trap}} = 1368 \), which is higher than \( \phi_{\text{max}} \). These protons, shown in the red line in figure 5(a), are not fully accelerated, and their end energy is not high, as is expected. For protons with an initial energy higher than \( \gamma_{\text{0 min}} \), they will be trapped and accelerated in the wakefield, such as the protons with \( \gamma_0 \approx 2 \) in the above simulation requiring the potential of \( \phi_{\text{trap}} = 128 \), which is smaller than \( \phi_{\text{max}} \). These protons shown in the blue line in figure 5(a) move with the bubble and gain high energy. The analysis result is in good agreement.
with the simulation results. Of course, the higher the initial energy, the shorter the acceleration time before they are dephased, and the less energy they gain. Therefore, the maximum potential of the bubble plays a key role for the trapping and acceleration. Figure 5(b) shows that the maximum potential \( \phi_{\text{max}} \) changes with the laser amplitude \( a_0 \) for different underdense plasma densities. That is, in order to obtain the high \( \phi_{\text{max}} \), we may choose high laser intensity and low plasma density. One point that should be noted in this case is that the bubble velocity will be higher; so, the required potential for trapping will be higher from equations (3) and (4).

The analysis shows that the LG laser pulse generates the focusing force in the transverse direction, which is crucial for the proton acceleration in the wakefield. Although the acceleration field around the \( x \)-axis is slightly weakened, the protons with an appropriate initial energy, which is related to the maximum potential of the acceleration field, can still be trapped and accelerated stably and can get nearly ten orders of energy gain.

It is necessary to have a much longer acceleration process to obtain higher energy protons. In the wakefield acceleration cases, it is an alternative way to prolong the acceleration distance by increasing the laser intensity or decreasing the plasma density, when the trapping condition is met. In the present case, protons with energy above 10 GeV can be obtained by increasing the LG laser pulse intensity and decreasing the initial energy of the witness protons or by decreasing the background plasma density but increasing the initial energy of witness protons simultaneously to make sure that ions can be trapped. To confirm this, we show another case by using 2D PIC simulations. In this case, \( a_0 = 141.4, n_0 = 8 \mu \text{m} \) and \( n_0 = 3 \times 10^{20} \text{ cm}^{-3} \). The initial energy is reduced to 500 MeV. The other parameters are the same with those in the 3D case. As shown in figure 6, the proton beam has also been well confined on the axis. Eventually, protons are accelerated to the peak energy of 12 GeV at \( t = 1.89 \text{ ps} \) when they are dephasing. At this time the laser pulse is nearly depleted.

For the proton acceleration in the wakefield, the acceleration distance that the trapped protons travel before they outrun the bubble, i.e. the dephasing length, which is approximated as \( L_{dp} \sim (1/4\pi^2) (a_0/\nu_{\text{th}})^{3/2} \lambda \) [22], is important because it is critical for the final energy of the accelerated protons. The laser pulse depletion length is another important factor, which is decided by the laser duration once the laser intensity and background plasma density are given.
Considering the conversion efficiency, the laser pulse duration can be adjusted to make the depletion length match the dephasing length.

In this scheme, the wakefield is \( \sim 10^{13} \text{ V m}^{-1} \), which is intense enough for proton acceleration. Beam loading induced by the witness proton with the number \( 10^9 \) has nearly no influence on the wakefield. Moreover, owing to the intense ponderomotive force in the transverse direction of the ultra-intense laser pulse, the on-axis ponderomotive force in the transverse direction of the ultra-intense laser pulse is stable during the laser propagation. Most of the protons are still controlled in the radius of 2 \( \mu \text{m} \) in the transverse direction after acceleration. Compared with the results before acceleration, the proton beam can be well confined near the axis during the acceleration process, and its transverse spot after acceleration is unchanged roughly, which is different from the case of the electron sheath oscillating in [24].

4. Conclusion

In conclusion, the witness proton acceleration in the wakefield driven by a LG_{10} laser pulse has been studied. Confining the protons near the acceleration axis is important for the continuous acceleration in the bubble regime. By using the LG_{10} laser pulse, a special bubble with a high density electron thread on the axis has been found in which an intense enough acceleration field in the longitudinal direction and a focusing field in the transverse direction for the protons coexist. The 3D PIC simulation results show that protons can be well confined near the axis and accelerated stably for a long time. The energy of the protons is increased to 7 GeV from 1 GeV.

In view of the real experiments, the witness protons can be obtained from the well-known radiation pressure acceleration regime in which the potential of the energy of the accelerated protons to reach GeV is promising, according to a large number of theoretical studies [2, 9, 11, 23]. Actually, the initial energy of witness protons can be smaller, which seems much easier using the present method if the wakefield is intense enough with a higher laser intensity or higher plasma density (confirmed in figure 6). On the other hand, in the present bubble structure, there are electrons both on-axis and near the walls of the bubble. The transverse force acts inward (focusing) for protons near the axis electron pillar and outward (defocusing) for protons near the electron walls. Therefore, there is an upper limit of the injected proton beam size to make the protons well confined on the axis, which is about half the radius of the bubble according to its transverse force distribution, as shown in figure 3(b). However, although the size of the witness proton beam is much larger than the radius of the electron sheath (such as the proton beam produced by RPA), the proton beam within the area of the half radius of the bubble can still be focused to the axis because of the existence of the transverse radial field. Another case (not presented in this paper) of the larger-sized (radius of 5 um) witness proton beam has been performed and has confirmed this. Additionally, obtainable high energy protons with the currently available laser level is realistic because they are easier to realize, and our study show that the present scheme still works for the lower intensity, such as \( a_0 \) around 20, but requires witness protons with higher initial energy. Moreover, the generation of such an intense LG_{10} laser pulse is critical for the present scheme. Fortunately, a potential approach has been proposed recently [30].
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