High-energy proton beam obtained by single high-power LG laser acceleration

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Abstract: We used 3D particle-in-cell (PIC) simulations to investigate the effect of a single high-energy Laguerre-Gaussian laser pulse interacting with an underdense plasma on the acceleration process of a proton beam. The single-beam LG laser drive solves the problem of the need for external proton injection and the synchronization of two laser pulses. The circularly polarized LG laser first takes protons out of the high-density plasma target and pre-accelerates them through the radiation pressure acceleration mechanism (RPA). Then, when the LG laser pulse enters the low-density plasma, a special cavity structure with electron columns will be formed due to the special transverse intensity distribution of the LG laser. The self-injected proton in the special cavity will be accelerated while being confined to the center and steadily accelerated by the tail field of the cavity at very long distances.3D PIC simulation results show when using power density when the LG laser is captured, the self-injected protons are accelerated to very high energies (the maximum energy of a proton is) and lower divergence.

Key words: proton acceleration, coda field acceleration, Laguerre Gaussian laser

1.introduction

Laser-driven high-energy proton beams have attracted much interest due to their extensive applications in scientific research. Protons with MeV or even GeV energy can be used directly or for laser nuclear physics1□Cancer treatment2or material preparation3et al application. Various schemes based on laser-driven mechanisms have been developed to obtain high-energy protons, such as sheath acceleration (TNSA)4□Radiation pressure Acceleration (RPA)5□Collisionless Impact Acceleration (CSA)6□and Laser Tailfield Acceleration (LWFA)7. TNSA and RPA are the best solutions for proton acceleration. At present, RPA mechanism driven by circularly polarized laser has become a research focus. Existing simulation and analytical studies have shown that the intensity of use in the RPA region exceeds the circularly polarized laser can obtain high-energy protons with cutoff energies of GeV89.

With conventional RPA, a laser pulse is incident on a thin solid target, and mass forces push the electrons forward, creating an accelerating field that pulls the protons forward. This acceleration mechanism can accelerate protons with low divergence Angle and high energy in a short time. However, whether the proton is accelerated by RPA or LWFA, due to the presence of a strong space charge field in the plasma10, Protons can't even accelerate over long distances. Therefore, it is very difficult to obtain protons with energies >5 GeV in the RPA region11. In addition, when the proton accelerates in the LWFA region, the radial electric field in the bubble will cause the proton to scatter if no additional binding force is applied. In order to solve the above problems, the simulation study proposes the use of LG lasers interacting with low-density plasmas to accelerate protons, as well as the use of two laser beams the LG laser and the super-Gaussian (SG) laser to accelerate protons12.However, both schemes have drawbacks. The former applies only to externally injected protons with GeV energy, and high quality preparation protons are required before acceleration can begin. The latter can achieve self-injection of protons, but the two laser pulses must be incident at a certain delay time. Therefore, adjusting the parameters of the appropriate two laser pulses also brings difficulties to the research and practical operation.

In this paper, we propose an improved proton acceleration scheme, that is, self-injection and acceleration of protons by a single CP-LG laser pulse driver. For ion acceleration, the most important processes are: ion implantation process and ion acceleration process. A circularly polarized LG laser incident on a solid density target pre-accelerates protons in the RPA region. When the LG laser enters the low-density plasma, the electron column is formed in the center of the bubble due to the special spatial distribution of the LG laser pulse electric field. Such a column of electrons provides a confining effect on the proton beam in the radial direction to ensure that protons can be accelerated over longer distances. Since the pre-accelerated protons in the RPA region always follow the laser pulse, the pre-accelerated protons can be captured well in the bubble region. We will analyze the acceleration process of the proton and the quality of the resulting proton through simulation.

2.Simulate Settings

The LG pulse is first incident on a solid target, pre-accelerates the protons, and then drives the proton beam in a low-density plasma to continue accelerating.

The simulation was carried out using 3D particle-in-cell (PIC) simulation code (EPOCH). The size of the simulation box is. The corresponding window has a 1600200200 lattice, a macro particle. Plasma solid target site ,, location, density , is the critical density of plasma.background low-density plasma located in, its density .

In this scheme, the Gaussian mode of the laser used in the simulation is LG_{10}mode, then the above expression is simplified as follows:

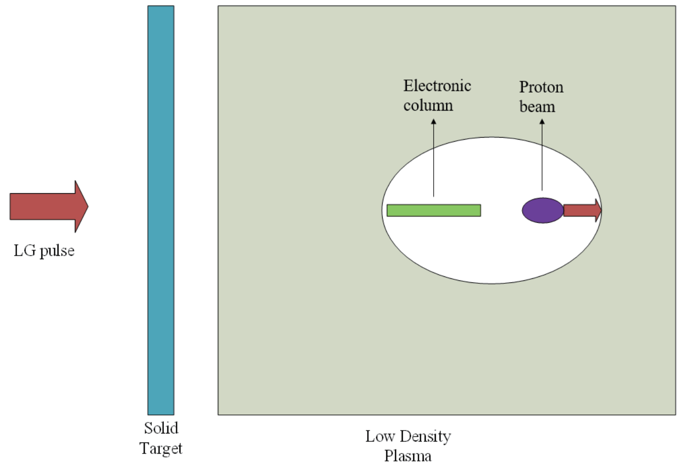

FIG.1 Schematic illustration of acceleration of a proton beam driven by an LG pulse

Among ,we can easily calculate the laser intensity at this position when r=0, So Laguerre-Gauss laser has a hollow electric field structure. We used in the simulation the peak intensity of the laser is, the corresponding wavelength of the laser pulse the normalization lose potential, Among lose potential where e is the number of electron charges, is the electronic mass, It's the laser frequency. It's the speed of light in a vacuum.

FIG. 1 Schematic diagram of proton beam acceleration driven by LG pulse. The LG pulse is first incident on a solid target, pre-accelerates the protons, and then drives the proton beam in a low-density plasma for sustained acceleration. As shown in Figure 1, the CP-LG laser pulse is incident from the left boundary and propagates to the right (positive X-axis). It interacts with the solid density target and then enters the low-density plasma where it continues to accelerate the protons.

3.Results and discussion

At the beginning of the simulation, The laser beam enters the simulation frame from the left boundary and subsequently interacts with the thin target, as shown in Figure 2(a). The radiation pressure of the intense laser pulse causes protons in the thin target to be pushed out of the back, pre-accelerating them. By t = 100 fs, the RPA process is basically complete, and the protons have been accelerated to hundreds due to the strong acceleration field MeV, As shown in Figure 2 (b). the laser beam is due to its peak intensity. It can easily penetrate thin targets, so it can continue in the X-axis direction after the forward propagation RPA processing. Since the density of the thin target is not very high, the laser pulse remains in its original state (i.e., neither splits nor exhausts), as shown in Figures 2 (c) and 2 (d). This is essential for the subsequent efficient acceleration of the proton, Because The laser pulse maintains the same electric field structure as before the interaction. When a Laguergauss (LG) laser beam passes through a low-density plasma, The laser's powerful mass force squeezes electrons near y=0, forming Figure 3. This structure exhibits a much higher electron density than the background plasma electrons. At the same time, electrons are expelled from the laser beam under the action of the dynamic force, thus forming a bubble structure. The combination of these factors in a low-density plasma leads to the formation of a unique bubble structure with electron columns.

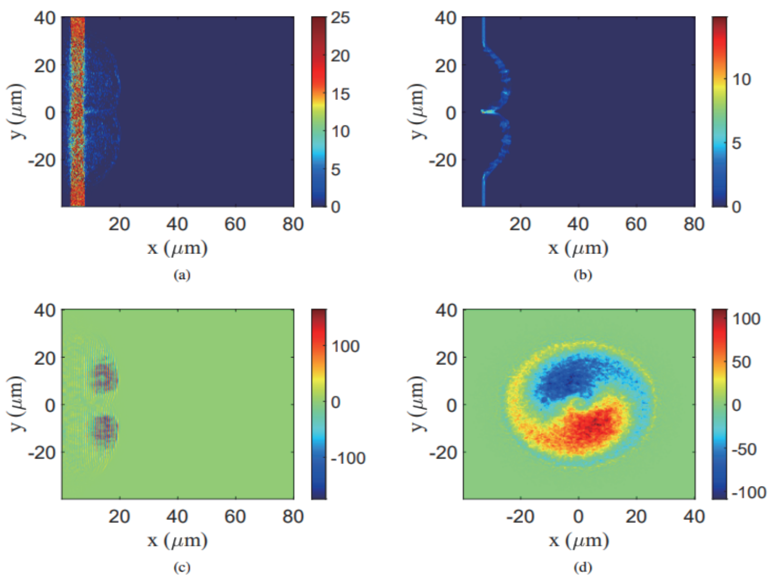

Figure 2 Laser radiation pressure accelerates protons

The presence of electron columns provides favorable conditions for the acceleration of protons in the bubble. In the radial direction, the special bubble structure with electron columns effectively reduces the dispersion of protons during acceleration. At the same time, in the axial direction, a strong acceleration field is generated towards the front of the bubble, as shown in Figure 3. if the transverse mass force of the laser beam is sufficiently strong, such as the laser intensity used in this simulation (), The electron column can then be compressed into a higher density electron filament, improving the laser tail field's ability to capture and accelerate protons over long distances. As shown in Figure 3 (b), the proton beam accelerates steadily at t=1.5ps, with no lateral divergence. When using the LG laser for the pre-acceleration phase of the proton, a radial confinement effect occurs when the proton accelerates in the RPA region. This is why LG lasers are superior to Gaussian lasers. When LG laser pulses interact with solid thin targets, they exhibit very strong limiting effects on both electrons and ions. The transverse dynamical force of the LG laser pulse can be quantitatively calculated using the dynamical potential model. The expression for the transverse qualitative force is as follows13.

According to this equation, there is a lateral mass force () locate Of the region,It takes the proton radially.On the other hand, in In the opposite region, transversely plasmic forces can bind protons along the radial direction.Therefore, the pre-accelerated proton is always able to remain near the y=0 axis, as shown in Figure 4(a), 4(b). Radial confinement of protons in the RPA region and the bubble region is the reason for the small proton divergence Angle (, t=1.5 ps), Figure 4 (c). In addition, the peak energy of a proton can reach 24 GeV (t=1.5 ps), as shown in Figure 4 (d).

4.Conclusion

This scheme effectively solves the problem that requires external proton injection and synchronization of two laser pulses. The lateral confinement of protons in the RPA region and the bubble region is achieved by using a peak intensity of the single LG laser pulse is achieved.This is due to the transverse electric field distribution of the laser pulse, which allows the protons to be confined to the RPA region and pre-acceleration. In the bubble region, unique bubble structures with electron columns are created to confine protons laterally and accelerate them efficiently. The 3D PIC code simulation results show that the proton reaches the peak energy of 24 GeV at t=1.5 ps and the divergence Angle is small, which is .This single LG laser pulse scheme optimizes the energy and spatial distribution of protons compared to the scheme using an externally injected proton beam and the scheme using two laser pulses (Gaussian pulse + LG pulse).

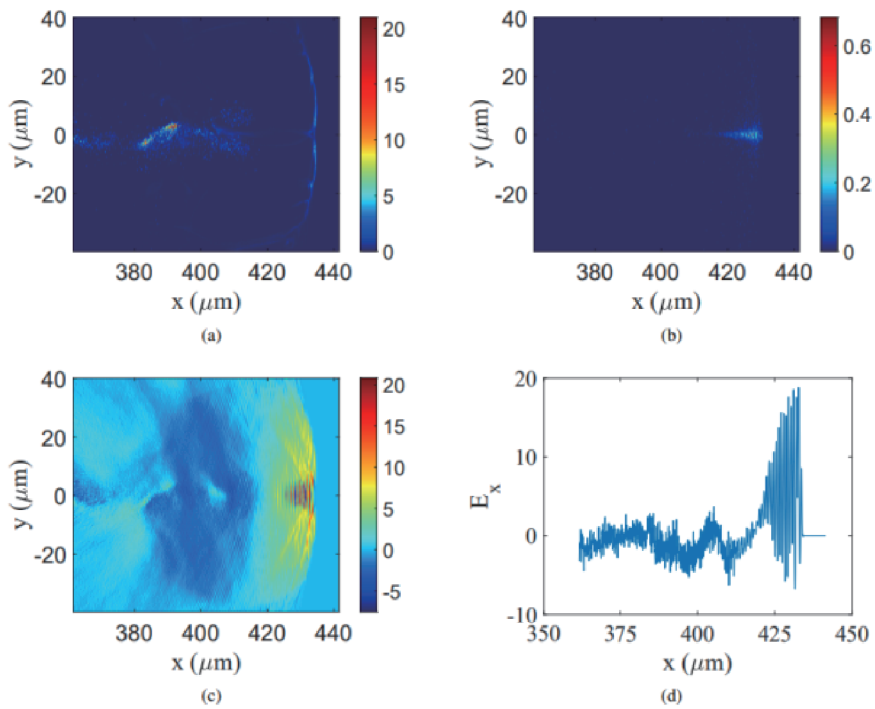

Figure 3 When the LG laser beam passes through a low-density plasma, the powerful mass force of the laser squeezes electrons near y=0

Figure 3 At t=1.5ps, when the LG laser beam penetrates the low-density plasma, protons are captured and subsequently accelerated within the bubble region. (a) The electron density distribution shows a unique bubble structure with electron columns (b) The density distribution of protons indicates that they are accelerating in the bubble region (c) The distribution of the accelerating electric field () indicates a strong accelerating field present in the front of the bubble region (d) The accelerating electric field strength at y=0 () indicates the acceleration field strength. These results confirm that the LG laser beam is capable of trapping and efficiently accelerating protons in the region of low density plasma bubbles.

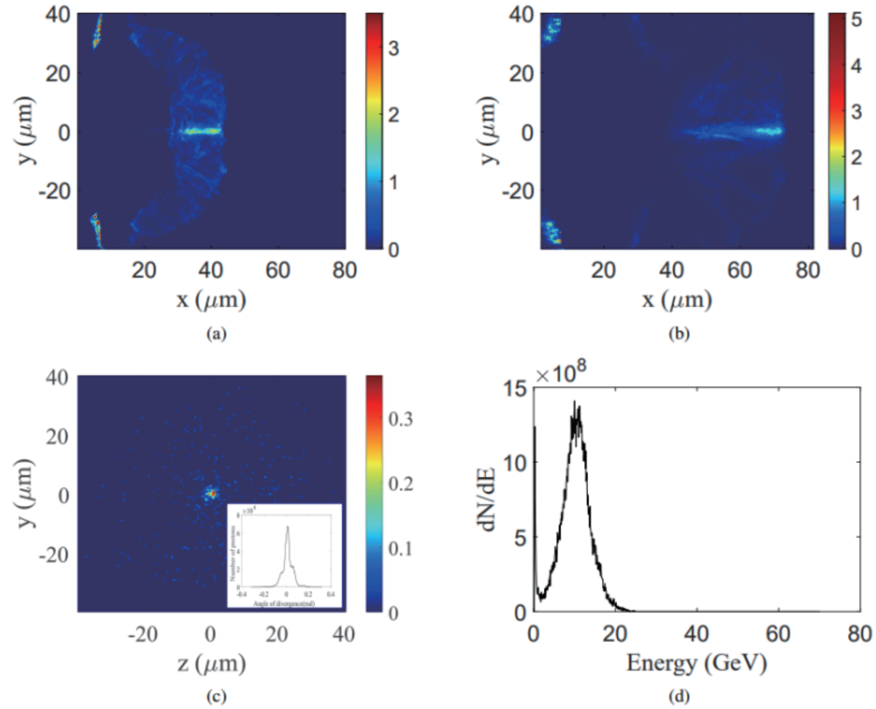

FIG. 4 (a) t=100fs, the density distribution of protons in the xy plane

(b) t=200fs, the density distribution of protons in the xy plane

(c) t=1.5fs, yz plane proton density distribution and proton divergence Angle distribution

(d) t=1.5ps, the energy distribution of the proton

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