Plasma zone plate for high-power lasers driven by a Laguerre–Gaussian beam

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Abstract
Plasma-based optics has emerged as an attractive alternative to traditional solid-state optics for high-power laser manipulation due to its higher damage threshold. In this work, we propose a plasma zone plate (PZP) driven by the ponderomotive force of a Laguerre–Gaussian beam when it irradiates an underdense plasma slice. We formulate the theory of the PZP and demonstrate its formation and functioning using particle-in-cell simulations. The proposed scheme may offer a new plasma-based method to manipulate high-power lasers.

Keywords: plasma zone plate, laser manipulation, plasma optics, nonlinear plasma dynamics, laser-plasma interaction

(Some figures may appear in colour only in the online journal)

1. Introduction

In the last few decades, the rapid development of revolutionary laser techniques, such as chirped pulse amplification [1] and optical parametric chirped pulse amplification [2], has significantly improved the peak intensity of lasers and opened up new avenues for fundamental research in fields such as strong field quantum electrodynamics [3, 4], high-energy-density physics [5] and relativistic optics [6]. The highest laser intensity available at the moment is delivered by high-power petawatt (PW) lasers [7] and can realize intensities up to \( \sim 10^{23} \text{ W cm}^{-2} \) after being focused [8]. With the increasing peak intensity of lasers, manipulation of such high-power lasers has become increasingly challenging because the size of the traditional solid-state optical components must be enlarged to avoid laser-induced thermal damage [9], which can be extremely costly and technically challenging for large-scale PW laser systems [10]. As a result, plasma-based optical components composed of free electrons and ions, which are not limited by optical damage as the traditional solid-state optical components, have become potential alternatives for high-power laser manipulation and have been extensively studied in recent years [11–23]. A series of plasma-based optical components and applications have been proposed, such as plasma gratings or photonic crystals with band structure [11–13], plasma holograms for focusing and mode conversion [14], plasma mirrors for probing strong field quantum electrodynamics [15, 16], plasma lenses for laser shaping [17], plasma waveplates for polarization manipulation [18–20] and plasma-based ellipsoidal mirror [21] and compound parabolic concentrator [22] with an intensity toleration over \( 10^{12} \text{ W cm}^{-2} \) for focusing lasers. Recently, Edwards et al demonstrated a highly-efficient plasma-based zone plate by two copropagating lasers which tolerates a maximum intensity of \( 10^{17} \text{ W cm}^{-2} \) [23]. The structure of the zone plate reminds us of the intensity patterns of Laguerre–Gaussian (LG) lasers.

LG beams, the eigensolution of the Helmholtz equation in a cylindrical coordinate system under the paraxial condition, are characterized by the azimuthal mode index \( l \) and the radial mode index \( p \), where \( l \) denotes the number of \( 2\pi \) phase cycles around the circumference and \( (p + 1) \) denotes the number of...
radial nodes in the mode profile [24]. Almost all the previous works on the interaction between LG lasers and plasma focus on optical angular momentum related properties, which are characterized by the azimuthal mode index \( l \) [25–28]. The intensity pattern of an LG beam with a nonzero \( l \) consists of \( p \) halos separated from each other by dark rings and a dark center.

In this work, we propose a plasma zone plate (PZP) driven by the ponderomotive force generated by an LG beam with a nonzero \( p \). As an eigenstate of electromagnetic wave in vacuum, the LG beam owns the advantage of stable propagation for a long distance. Compared to the previously proposed two-beam beating scheme [23], the proposed method relaxes the engineering complexity for potential experiments. The formation and functioning of PZP are considered theoretically and verified by numerical and particle-in-cell (PIC) simulations.

The paper is organized as follows: proof-of-principle demonstrations of our scheme by 3D-PIC simulations are shown in section 2. The theoretical model of PZP formation is presented in section 3. The formation process is divided into three main stages and a detailed comparison between the theoretical analysis and simulation results is demonstrated. The functioning of the PZP is specified in section 4. On the one hand, the theoretical model and typical examples for focusing infrared and terahertz (THz) lights are presented. On the other hand, the more realistic scenario of an obliquely incident probe beam is discussed. Conclusions are summarized in section 5.

2. Proof-of-principle PIC demonstrations

First of all, we present proof-of-principle demonstrations of our scheme using 3D-PIC simulations by the code EPOCH [29] to illustrate the formation and functioning of a typical PZP. The schematic is shown in figure 1(a).

In the cylindrical coordinate system, the complex amplitude of the electric field of a circularly polarized (CP) LG laser can be expressed as:

\[
E_{x,y} = \frac{E_p}{C_p} \exp \left( -\frac{r^2}{w_p^2} \right) \left( \frac{\sqrt{2}r}{w_p} \right)^l L^l_p \left( \frac{2r^2}{w_p^2} \right) \times \exp [i(kz + l\phi + \varphi_{x,y})] \tag{1}
\]

where \( E_p \) is the peak amplitude of the electric field, \( C_p \) is the normalization constant, \( w_p \) is the beam radius, \( L^l_p \) is the Laguerre polynomial, \( \varphi_{x,y} \) is the initial phase of \( x/y \) polarization, and \( k \) is the wavenumber. Here, our analysis is within the Rayleigh range so that the diffraction can be neglected [30].

A CP LG beam (\( \lambda_p = 1 \mu m, l = 2, p = 4 \)), the intensity of which is shown in figure 1(b), is launched from the \(-z\) boundary as the pump beam to irradiate a thin plasma slice for demonstration. The beam radius is \( w_p = 10 \mu m \) and the maximum intensity is \( 2.7 \times 10^{18} \) W cm\(^{-2}\). The plasma slice consists of a constant density slab of length \( 2\lambda_p \) with Gaussian density ramps of length \( 1\lambda_p \) at each side along the \( z \)-direction while uniformly distributed on the \( x/y \) plane. The maximum density is set to be \( n_d = 0.3n_c(\lambda_p) \), where \( n_c(\lambda) [\text{cm}^{-3}] = 1.12 \times 10^{21}/\lambda^2(\mu m) \) is the critical density for the laser with wavelength \( \lambda \). Such a thin near-critical density plasma can be created by carbon nanotube foams [31, 32]. In the PIC simulations, the ions are set to be \( q_i = e \) and \( m_i = 100m_e \) (\( e \): the elementary charge, \( m_e \): the electron mass) to reduce the simulation cost. The plasma temperature is \( T_e = 25 \) eV, \( T_i = 2.5 \) eV. The dimensions of the simulation box are \( L_x \times L_y \times L_z = 160 \mu m \times 160 \mu m \times 40 \mu m \) and the spatial resolutions are \( \Delta x = \Delta y = 0.25 \mu m \) and \( \Delta z = 0.1 \mu m \). The plasma slice is placed at the center of the simulation box and padded on both sides with sufficiently long vacuum regions.

As the pump beam interacts with the plasma, an annular density modulation starts to develop and reaches the maximum at around 4 ps, which is shown in figure 1(c). Then a CP probe beam (\( \lambda_b = 1 \mu m \)) is launched into this modulated plasma slice. Figure 1(d) shows the intensity distribution of the probe beam through its propagation. The modulated plasma functions as a PZP, which magnifies the intensity of the incoming probe beam up to approximately two orders of magnitude at several foci. Such a multi-focal laser field structure is the typical intensity structure after traversing the Fresnel zone plate (FZP). In the following, we formulated the theoretical model for the formation of PZP and verified it by simulations in detail.

3. Formation of PZP

Considering a non-relativistic CP LG laser traveling in the \( z \)-direction as the pump beam through an initially homogeneous underdense plasma consisting of electrons (charge \(-e\), mass \( m_e \) and density \( n_{eo} \)) and ions (charge \( Z_e \), mass \( m_i \) and density \( n_{io} = n_{eo}/Z_e \)). In the cylindrical coordinate system, the LG laser intensity is only related to \( r \), i.e. \( I = I_0 f(r) \) where \( I_0 = \sqrt{\epsilon/\mu}E_p^2 \) is the maximum intensity (\( \epsilon \) is the permittivity and \( \mu \) is the magnetic permeability) and \( f(r) \) is the normalized distribution function. Introducing the dimensionless laser amplitude \( a_p = E_p/\omega m_c c \), where \( \omega \) is the laser frequency and \( c \) is the speed of light in vacuum, the ponderomotive force on the electrons can be expressed as the negative gradient of the ponderomotive potential \( \phi_p = \frac{q_i^2}{2}m_e c^2 f(r) \) [33]:

\[
F_p^e = -\frac{q_i^2}{2}m_e c^2 \nabla f(r). \tag{2}
\]

The ponderomotive force on the ions is negligible since it is smaller than that on the electrons by a factor \( Z_e^2 m_e/m_i \) [34]. The density evolution is governed by the momentum equations and continuity equations of electrons and ions:

\[
n_e \frac{\partial v_e}{\partial t} + (v_e \cdot \nabla) v_e = n_e e \nabla \phi + n_e F_p^e - \nabla p_e \tag{3}
\]

\[
n_i m_i \frac{\partial v_i}{\partial t} + (v_i \cdot \nabla) v_i = -n_i Z_e \nabla \phi - \nabla p_i \tag{4}
\]
\[ \frac{\partial n_e}{\partial t} + \nabla \cdot (n_e \mathbf{v}_e) = 0 \]  

\[ \frac{\partial n_i}{\partial t} + \nabla \cdot (n_i \mathbf{v}_i) = 0 \]  

where \( \nabla p_\alpha (\alpha = i, e) \) is the thermal pressure term introduced according to the adiabatic law, which implies \( p_\alpha n_\alpha^{-\gamma} = \text{const} \) with \( p_\alpha = n_\alpha T_\alpha \), where \( T_\alpha \) is the particle temperature and \( \gamma \) is the adiabatic index \([35]\). \( \phi \) is the electrostatic charge-separation field generated by the Poisson equation:

\[ \nabla^2 \phi = \frac{e}{\epsilon_0} (n_e - Z n_i). \]  

Let \( \delta n_\alpha = (n_\alpha - n_{\alpha 0})/n_{\alpha 0} \) be the normalized density variation. The temporal evolution can be divided into three stages. Stage I is the beginning of the laser–plasma interaction: ions are assumed to be stationary and the normalized electron density variation is much less than unity, i.e. \( \delta n_i \approx 0, \delta n_e \ll 1 \). During this stage, an electrostatic charge-separation field is generated to balance the ponderomotive force. In stage II and III, the ions move together with the electrons driven by the charge-separation field. We define the period when \( \delta n_i, \delta n_e \ll 1 \) as stage II and the period when \( \delta n_i, \delta n_e \gtrsim 1 \) as stage III. In the following, we formulate the theoretical model for the density evolutions in each stage, and verify it with an example PIC simulation, the results of which are shown in figure 2.

In stage I, the ions are assumed to be stationary due to their large inertial mass. Since \( \delta n_e \ll 1 \), the thermal pressure \( \nabla p_e = -\nabla(n_e T_e) \) and the convective term \( n_e m_e (\mathbf{v}_e \cdot \nabla) \mathbf{v}_e \) of electrons are negligible. Therefore, the fluid equations of electrons can be linearized as:

\[ \frac{\partial \delta n_e}{\partial t} + \nabla \cdot \mathbf{v}_e = 0 \]  

\[ \frac{\partial \mathbf{v}_e}{\partial t} = \frac{e}{m_e} \nabla \phi + \mathbf{F}_e^m. \]  

Combining equations (7)–(9), one finds the normalized electron density variation as:

\[ \delta n_e = \frac{\omega_e^2 \varepsilon_0^2}{2 \omega_{pe}^2} \nabla^2 f(r) \]  

where \( \omega_{pe} \) is the electron plasma frequency. The comparison between the theory and the example simulation at \( t = 0.125 \) ps is shown in figure 2(b), where ions are still almost homogeneous, and the electron density variation is in accordance with the theory.

As the electrostatic charge-separation field is created in stage I, the ions are driven to move together with the electrons. During this stage, the electrons are assumed to remain in force equilibrium while the ion density variation becomes non-negligible, thus \( \delta n_i (r) - Z \delta n_e (r) = \frac{\varepsilon_0^2}{\omega_{pe}^2} \nabla^2 f(r) \). From the linearized fluid equations of ions:

\[ \frac{\partial \delta n_i}{\partial t} + \nabla \cdot \mathbf{v}_i = 0 \]  

Figure 1. (a) Schematic of a PZP. An LG beam \( (l = 2, p = 4) \) is launched into the plasma slice and generates a PZP. At a delayed time, a probe beam is focused by the PZP. (b) Intensity pattern for the pump beam. (c) Transverse density distribution of the PZP. (d) The laser intensity of the probe beam before, during, and after the interaction with PZP. The white dotted lines \((z = 18.2/21.8 \mu m)\) represent the position of the PZP.
Figure 2. Example PIC simulation: pump beam: $\lambda_p = 1 \, \mu$m, $l = 2$, $p = 2$, $w_p = 5 \, \mu$m, plasma: $n_{e0} = 10^{-4} n_c(\lambda_p)$. The initial density in the example simulation is set to be as low as $n_{e0} = 10^{-4} n_c(\lambda_p)$ to obtain an observable electron density variation in stage I according to equation (10). (a) Transverse evolution of the ion density. The white dotted lines indicate the characteristic times of stage I ($t = 0.125$ ps), stage II ($t = 1$ ps) and stage III ($t = 4$ ps). (b) Blue line: theoretical electron density variation of stage I. Orange line: electron density variation from PIC simulation. Green line: ion density variation from PIC simulation. (c) Blue line: theoretical ion density variation of stage II. Green line: ion density variation from PIC simulation. (d) Blue line: ion density variation from numerical simulation. Green line: ion density variation from PIC simulation.

\[
\frac{\partial v_i}{\partial t} = -\frac{Z e}{m_i} \nabla \phi \tag{12}
\]

one finds the spatiotemporal evolution of the ion density:

\[
\delta n_i = \frac{Z a_2^2 c^2}{4} \frac{m_e}{m_i} \nabla^2 f(r) r^2. \tag{13}
\]

Comparing equations (10) and (13), it is recognized that the electron and ion density variations follow the same spatial pattern, which is proportional to $\nabla^2 f(r)$. Therefore, an annular density variation is obtained, as can be seen from figures 2(b) and (c). The comparison between the example simulation and the theory in stage II ($t = 1$ ps) is shown in figure 2(c) and still exhibits a fair conformity.

As the normalized density variations continue to grow close to unity, the divergence of the particle flux $\nabla \cdot (n_{\alpha} v_{\alpha})$ ($\alpha = i, e$) cannot be simplified as $n_{i0} \nabla \cdot v_i$ any more and the thermal pressure becomes non-negligible. Therefore, the linearized approximation is no longer valid and thus the density variations are no longer theoretically analytic, we define this stage as stage III. Combining equations (3) and (4) and neglecting electron momentum [36] yields

\[
\frac{dv_i}{dr} = -\frac{Z a_2^2 c^2 m_e}{2 m_i} \nabla f(r) - \frac{\nabla (p_e + p_i)}{n_i m_i}. \tag{14}
\]

It is noted that the initially negligible thermal pressure becomes comparable to the electrostatic force at $|\delta n_i| \sim \left| \frac{Z a_2^2 c^2}{2 a_2^2} \right|^2$. According to (14), ions will be driven to the troughs of laser intensity and so with the electrons. Qualitatively speaking, the density variations in stage III are negatively correlated with $f(r)$, while proportional to $\nabla^2 f(r)$ in stage I and II. This can be identified by the density variation develops from proportional to $\nabla^2 f(r)$ shown in figure 2(c) to negatively correlated with $f(r)$ shown in figure 2(d), which is marked by the emergence of the density peak at $x = 0, y = 0$ at around 3 ps as shown in figure 2(a). As the nonlinear density variation in stage III is analytically difficult to derive, we developed a particle-fluid program [37] to numerically calculate the ion density evolution based on equation (14). A comparison of the ion density in stage III ($t = 4$ ps) between our particle-fluid program and the example PIC simulation is presented in figure 2(d). Although equation (13) is not able to precisely...
describe the density evolution in stage III, it allows us to estimate the pulse duration requirement for obtaining a substantial plasma density variation as \( \tau \approx \frac{n_0}{c \sqrt{\frac{m_e}{\mu}}}. \) Nonlinear laser-plasma instabilities, such as stimulated Brillouin instability, may take place at the early stage of the laser plasma interaction, but the particles would gradually be transversely driven out of the high-intensity regions by the ponderomotive force and the laser-plasma instabilities would then be suppressed.

The modulated plasma obtained eventually is composed of alternating high and low density rings corresponding to the alternating dark and bright rings of the incident LG beam. According to the dispersion relation of electromagnetic waves in plasma [38], such a density distribution can be interpreted as an annular refractive index structure with alternating low and high refractive index rings, thus we regard the obtained modulated plasma as a PZP.

### 4. Functioning of PZP

Considering a CP probe beam normally incident on the PZP and approximate the plasma as a typical medium, the refraction of the probe beam is governed by [39]:

\[
\left(\frac{\partial^2}{\partial y^2} - c^2 \nabla^2\right)a_b = -\frac{n_b c^2 a_0}{\gamma_e m_e} \partial_t \phi
\]

(15)

where \(a_b\) is the dimensionless laser amplitude in each polarization of the probe beam, \(\epsilon_0\) is the vacuum permittivity and \(\gamma\) is the relativistic factor given by \(\gamma = \sqrt{1 + \frac{a_0^2}{c^2}}\). The corresponding refractive index is given by \(N = \sqrt{1 - \frac{c^2}{\gamma c^2} - \frac{\partial \phi}{\partial y}}\). Thus, the alternating high and low density rings are alternating low and high refractive index zones for the probe beam. During propagation through the PZP, most of the energy of the probe beam will be refracted to the high refractive index rings and a phase shift is generated between adjacent rings. Let \(N_l\) and \(N_h\) be the characteristic low and high refractive indexes of PZP, \(\Delta r\) be the characteristic distance between adjacent rings and \(k_0\) be the vacuum wavenumber of the probe beam. The characteristic thickness to produce a significant amplitude modulation or a phase shift of \(\pi\) between adjacent rings can be given by [23, 40]:

\[
L_a = \left(\frac{N_h^2}{N_l^2} - 1\right)^{-\frac{1}{2}} \Delta r
\]

(16)

\[
L_\phi = \frac{\pi}{(N_h - N_l)k_0}.
\]

(17)

If the thickness of the PZP \(D \gtrsim L_a\), the amplitude modulation plays the leading role and the incident beam would be modulated into a light of alternating bright and dark rings, and the PZP is regarded as an amplitude zone plate. Otherwise, if \(D \gtrsim L_\phi\), the emergent light is composed of alternating rings with phase shift at the order of \(\pi\), corresponding to a phase zone plate. The PZP developed by Edwards et al is a sinusoidal zone plate created by two copropagating lasers that realizes one highly-efficient focus with Bragg resonance [41]. For the PZP created by an LG laser, several foci are produced along the optical axis by the interference of different rings [42]. Since both \(L_a\) and \(L_\phi\) are negatively correlated with the refraction index difference, PZP can also be formed by a thicker plasma slice with a smaller density, which might be easier to realize in experiments.

In the PIC verification simulation, a CP probe beam \((\lambda_0 = 1\ \mu m, a_0 = 0.5)\) with a maximum intensity of \(6.8 \times 10^{18} \text{ W cm}^{-2}\) is launched into the PZP obtained in section 2 as shown in figure 1(d). The intensity distribution on the optical axis is presented by the blue solid line in figure 3(a), which indicates that the PZP magnifies the intensity of the incoming probe beam up to a maximum of approximately two orders of magnitude at several foci. The energy efficiency at each focus is around 4%, which is lower than the first order efficiency (10%) of amplitude zone plate [43] considering the fact that the PZP created by an LG laser is not ideal and the energy is dispersed to different orders. The maximum intensity obtained is about \(9 \times 10^{19} \text{ W cm}^{-2}\). The horizontal and vertical dimensions of the spot size are of the same order of the probe wavelength and increase with increasing focal length, the same pattern as in the conventional FZP [44]. A contrast simulation of the PZP by the pump pulse with \(p = 2\) is conducted and a similar focused probe field structure is obtained, as shown by the black dashed line in figure 3(a). The result indicates that the maximum magnification increases with \(p\), since LG beams of higher \(p\) generate more alternating rings corresponding to zone plates of higher orders. The LG-light-modulated plasma slice functions as an FZP to focus the probe beam at multiple foci.

To manipulate a probe beam with a given wavelength \(\lambda_b\), the plasma density should generally be on the order of \(n_e \sim 0.1 n_c(\lambda_b)\) to realize significant modulation of the probe beam during its propagation, and the pump beam should be with a frequency higher than the plasma frequency. Therefore, one can create a PZP designed to manipulate lasers of longer wavelength with a pump beam of a shorter wavelength and larger spot size with an extremely underdense plasma. For instance, one can use a pump beam of a wavelength on the order of micrometers and a beam waist on the order of millimeters, to modulate an extremely underdense plasma whose density is set to be on the order of the critical density of THz lasers to produce a zone plate for THz laser manipulation. An exemplary simulation is conducted where a 10 \(\mu\text{m}\) LG laser is launched into a homogeneous plasma with density of \(n_{e0} = 3.35 \times 10^{16} \text{ cm}^{-3}\) and thickness of 200 \(\mu\text{m}\) to create a PZP for modulating a THz probe beam \((\lambda_b = 100 \mu\text{m}, \nu = 3 \text{ THz})\). The focusing result on the optical axis is shown by the purple dash-dotted line in figure 3(a). The given scheme may pave a new way for THz and visible laser manipulation at higher intensities.

As the probe beam approaches the relativistic intensity \((a_0 \sim 1)\), the longitudinal acceleration of electrons by the probe beam becomes significant [39] and may damage the PZP structure. Therefore, the PZP is only able to modulate short
Figure 3. (a) Magnification of the probe beam on the optical axis. Blue solid line: the PZP generated by an $l = 2, p = 4$ LG laser in section 2. Black dashed line: the PZP generated by an $l = 2, p = 2$ LG laser. Purple dash-dotted line: THz PZP, probe beam: $\lambda_b = 100 \mu m$, $\nu = 3$ THz, $I_0 = 6.8 \times 10^{13} \text{ W cm}^{-2}$. (b) The laser intensity of a CP relativistic probe pulse ($\lambda_b = 1 \mu m$, $a_b = 5$, $I_0 = 6.8 \times 10^{19} \text{ W cm}^{-2}$) after the interaction with a high-density PZP. (c) The laser intensity of a $15^\circ$ obliquely incident probe beam before, during, and after the interaction with PZP. The white dotted lines represent the location of the PZP.

5. Conclusions

In this manuscript, we propose to use an LG beam to generate a plasma-based zone plate for high power laser manipulation. The formation of PZP is modeled to be divided into three stages from the physical characteristics and the density evolutions in each stage are formulated. We verified our model by PIC and numerical simulations and obtained the annular density distribution composed of alternating rings of high and low densities. The obtained plasma density structure can be analogized to a zone plate to manipulate high power lasers. The functioning of PZP is verified by simulations with both normally and obliquely incident probe beams. Multi-focal intensity distributions are obtained which is consistent with the characteristics of traditional FZP.

In previous simulations, both the pump beam and the probe beam are normally incident onto the plasma slice for demonstration. Considering traditional FZP bears a certain robustness to the incident angle [45], we carried out a contrast simulation launching an obliquely incident probe beam with an incident angle of $15^\circ$ to the $x$ direction into the PZP in section 2. The intensity distribution in the longitudinal plane is shown in figure 3(c). Comparing to that of the normally incident case shown in figure 1(d), it is obvious that the foci are tilted with the incident angle while the focal lengths and magnifications remain almost the same as the normally incident case, which is consistent with the characteristics of traditional FZP.
two orders in the simulations. The proposed PZP is a new addition to the plasma-based class of optical elements for manipulating high-power lasers to obtain a multi-focal field structure, which owns the potential applications to various scenarios like laser drilling, cutting and particle acceleration.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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