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Self-focusing up to the incident laser wavelength by an appropriate density ramp

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Abstract

This work is devoted to improving relativistic self-focusing of intense laser beam in underdense unmagnetized plasma. New density profiles are introduced to achieve beam width parameter up to the wavelength of the propagating laser. By investigating variations of the beam width parameter in presence of different density profiles it is found that the beam width parameter is considerably decreased for the introduced density ramp comparing with uniform density and earlier introduced density ramp profiles. By using this new density profile high intensity laser pulses are guided over several Rayleigh lengths with extremely small beam width parameter.

Keywords: Density ramp; Propagating laser; Self-focusing; Underdense plasma; Unmagnetized plasma

INTRODUCTION

Since the first suggestion of Askarian (1962), self-focusing is an extensively studied phenomenon in the field of high intensity laser interaction with nonlinear media. When laser intensity exceeds the critical power $P_{cr} \cong 17\ (\omega/\omega_p)^2$ GW, which ω and ω_p are the laser frequency and the plasma frequency, respectively (Sun *et al.*, 1987), quiver motion of the generated relativistic electrons increase the mass of electrons. As a consequence, transverse gradient of the refractive index leads to confinement of the laser beam to the propagation axes and decreases the beam width parameter that gives rise to the relativistic self-focusing (Hora *et al.*, 1975; Osman *et al.*, 2000). Due to mass increase in relativistic self-focusing, the electron mass replaced by $m_0\gamma$ where $\gamma = (1 + a^2/2)^{1/2}$ is relativistic factor, $a = e|E|/(m_0 c\omega)$ is normalized laser amplitude and E, e, m_0 are the amplitude of the laser electric field, the electron charge, and the electron rest mass, respectively. Therefore, the plasma dielectric function modified as $\varepsilon = 1 - \omega_p^2/\gamma\omega^2$, where $\omega_p = (4\pi n_e e^2/m_0\gamma)^{1/2}$ is the plasma frequency (Boyd *et al.*, 2008). The ponderomotive force also causes nonlinear electron perturbation that exerts a radial force and expels the electrons radialy outward from the intense laser beam axes, which ends to ponderomotive self-focusing (Mori *et al.*, 1988; Perkins & Valeo, 1974). Ponderomotive self-focusing causes decreasing of electron density and increasing the refractive index.

Resent advances in ultra-intense short-pulse lasers and their numerous applications stimulated the research activities in this field such as generation of high-energy electron and ion beams and their acceleration (Leemans *et al.*, 2006; Láska *et al.*, 2006; Lihua *et al.*, 2004; Geddes, 2005; Hoffmann *et al.*, 2005; Schlenvoigt *et al.*, 2008; Xie *et al.*, 2009; Zhou *et al.,* 2007), monoenergetic electron beam (Fature *et al.*, 2004; Singh *et al.*, 2008; Sadighi-Bonabi *et al.*, 2009*a*, 2009*b*, 2010*a*, 2010*b*), monoenergetic ion beam generation (Hegelich *et al.*, 2006), X-ray emission and X-ray lasers (Zhang *et al.*, 1998), harmonic generation (Butylkin & Fedorova, 1994), fusion with the fast ignition scheme (Lalousis & Hora, 1983; Hora, 2004, 2009; Hora *et al.*, 2009; Ghoranneviss *et al.*, 2008; Yazdani *et al.*, 2009; Sadighi-Bonabi *et al.*, 2010*c*, 2010*d*). These lasers are also used in the transmutation of hazardous radioactive wastes to valuable nuclear medicine (Sadighi-Bonabi & Kokabi, 2006; Sadighi-Bonabi *et al.*, 2010*e*; Sadighi & Sadighi-Bonabi, 2010).

In the entire above mentioned ultra-intense laser interactions, self-focusing has an important role and it should be carefully studied. In order to guide high intensity laser pulses over several Rayleigh lengths, it is important to employ self-focusing by a defined density profile. This achievement can have very fundamental impact in the recent advances of laser-plasma interaction and fast ignition

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systems. Self-focusing effects have been observed in laser-plasma interaction that enables the laser beam to propagate over several Rayleigh lengths (Boyd *et al.*, 2008; Schlenvoigt *et al.*, 2008). Self-focusing has been investigated in the interaction of laser beam with homogenous and inhomogeneous plasma (Upadhyay *et al.*, 2002; Varshney *et al.*, 2006; Kaur & Sharma, 2009; Sharma & Kourakis, 2010).

In this work, a complete study of density ramp profiles is presented and the self-focusing of laser beam along the propagation axis in axially inhomogeneous plasma is simulated. It is shown that with the introduced density ramp profile and by optimizing the laser and plasma parameters, the laser beam width parameter is reduced up to the laser wavelength.

VARIATION OF BEAM WIDTH PARAMETER

For investigating of electron density variation of unmagnetized cold plasm, the propagating of a Gaussian laser beam $E = \hat{x}A\, e^{-i(\omega t - k_0 z)}$ in a cylindrical coordinate system is considered, where $k_0(z) = (\omega_0/c)\omega 0/c)\varepsilon_0^{1/2}$ and ε_0 is the plasma dielectric constant. Following the Tripathi *et al.* (2005) approach, at $z > 0$ one have $a^2 = (a_0^2/f^2)\exp(-r^2/r_0^2 f^2)$, where f is the laser beam width parameter and $a_0 = eA_0/(m\omega c)$ is the laser intensity parameter.

As the Gaussian beam have an intensity gradient along its cross-section, the radial ponderomotive force pushes the electrons outward of propagation axis, on the time scale of a plasma period ω_p^{-1} and creates a radial space charge field of $E_s = -\nabla\varphi_s$, therefore, considering Poisson's equation, electron density modified as:

$$n_e = n_{e0} + (1/4\pi e)\nabla_\perp^2 \varphi_s. \tag{1}$$

Where φ_s is the electric potential, which is due to the radial space charge. In quasi-steady state one can have $F_p = -\nabla\varphi_p = eE_s$, where φ_p is the radial ponderomotive force and it is defined as

$$\varphi_p = -(mc^2/e)((1 + a^2/2)^{1/2} - 1). \tag{2}$$

Therefore, the modified electron density is obtained similar to the works of Tripathi *et al.* (2005), Gupta *et al.* (2007*a*), and Sadighi-Bonabi *et al.* (2010*f*, 2010*g*):

$$n_e = n_{e0}(z)\left\{1 - \frac{c^2}{\omega_p^2 r_0^2 f^2}\frac{a^2}{(1 + a^2/2)^{0.5}} \times 1 - \left(\frac{r^2}{r_0^2 f^2}\frac{1 + a^2/4}{1 + a^2/2}\right)\right\}. \tag{3}$$

And the dielectric constant of plasma is obtained as

$$\varepsilon = 1 - \omega_p^2/\gamma\omega^2 = 1 - \left(\frac{4\pi n_0(z)\left\{1 - \frac{c^2}{\omega_p^2 r_0^2 f^2}\frac{a^2}{(1 + a^2/2)^{0.5}} \times 1 - \left(\frac{r^2}{r_0^2 f^2}\frac{1 + a^2/4}{1 + a^2/2}\right)\right\}e^2}{m_0\sqrt{1 + \frac{a^2}{2}}\,\omega^2}\right)^{1/2}, \tag{4}$$

in paraxial approximation ($r_2 \ll r_0^2 f_2$), the dielectric constant of plasma can be expanded as $\varepsilon = \varepsilon_0 - r^2/r_0^2$. As a result expanding of in this approximation, leads to:

$$\varepsilon \cong \left(1 - \frac{\omega_p^2}{\omega^2}\frac{\sqrt{2}}{\sqrt{2 + a^2}} + \frac{c^2 a^2}{\omega^2\left(1 + \frac{a^2}{2}\right) r_0^2 f^2}\right) - \left\{\left(\frac{\sqrt{2}}{2}\frac{\omega_p^2}{\omega^2}\frac{a^2}{\sqrt[3]{2 + a^2}} + \frac{c^2 a4}{\omega^2}\frac{1}{f^4 r_0^2 (2 + a^2)^2} + \frac{c^2 a4}{\omega^2 f^4}\frac{1}{(2 + a^2)\left(1 + \frac{a^2}{2}\right)} + \frac{4c^2 a^2}{\omega^2}\frac{1}{f^8 r_0^2 (2 + a^2)^2}\right)\right\} \times \frac{r^2}{r_0^2}. \tag{5}$$

Then expansion coefficients are obtained as:

$$\varepsilon_0 = 1 - \frac{\omega_p^2}{\omega^2}\left(\frac{1}{(1 + a^2/2)^{1/2}}\right) + \frac{c^2 a^2}{\omega^2 r_0^2 f^2 (1 + a^2/2)},$$
$$\phi = \frac{\omega_p^2}{4\omega^2}\frac{a^2}{f^2(1 + a^2/2)^{3/2}}\left(1 + \frac{c^2(8 + a^2)}{r_0^2\omega_p^2 f^2 (1 + a^2/2)^{1/2}}\right). \tag{6}$$

Regarding the wave equation approaches (Gupta *et al.*, 2007*a*); the second order boundary equation for the laser beam width parameter is obtained as:

$$\frac{\partial^2 f}{\partial \xi^2} = \frac{1}{f^3} - \frac{1}{2\varepsilon_0}\frac{\partial f}{\partial \xi}\frac{\partial \varepsilon_0}{\partial \xi} - \frac{R_d^2}{r_0^2\,\varepsilon_0}\phi f. \tag{7}$$

Where $\xi = z/R_d$ is dimensionless propagation length, with $R_d = \omega r_0^2/c$ as Rayleigh length. The first term on the right-hand side of Eq. (7) is due to the diffraction effect, the second term is due to the plasma inhomogeneities, and the last term is the nonlinear term that is responsible for relativistic self-focusing. Using initial boundary condition at $z = 0$ as $f = 1$ and initial plane front wave ($df/d\xi = 0$), one can solve this equation and investigate changing of the beam width parameter along the laser propagation in plasma.

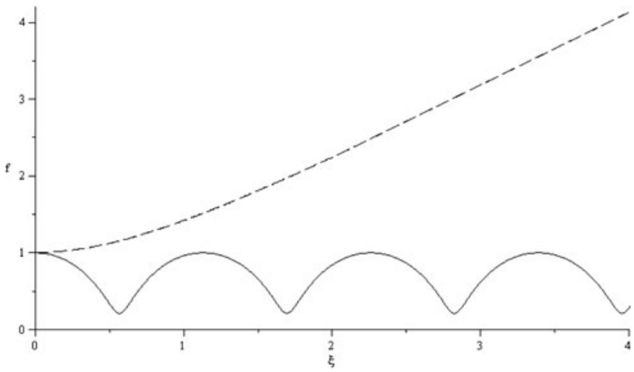

Fig. 1. Dependence of beam width parameter f on distance of propagation in underdense plasma neglecting self-focusing (dash curve) and for self-focusing with uniform electron density (solid curve).

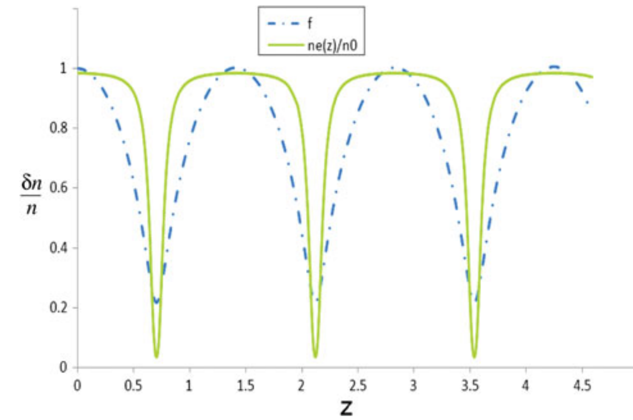

Fig. 3. (Color online) The changes of electron density (solid curve) and beam width parameter along laser beam propagation (z).

The critical laser relativistic intensity of $I = 1.21 \times 10^{18}$ (w/cm^2) is assumed for Nd:Glass laser wavelength $\lambda = 1.06$ µm and initial laser spot size chosen as $r_0 = 10\lambda = 10.6$ µm. For propagation of laser in plasma without reflecting, electron density must be regarded less than the critical density $n_{\rm cr} = (\omega^2 m/4\pi e^2) \simeq 10^{21}(\text{cm}^{-3})$. Therefore, laser frequency must be larger than the plasma frequency.

Figure 1 shows the plots of Eq. (7) for propagation of the laser beam in plasma with constant density ($n_{e0} = n_0$), by considering the self-focusing effect (solid curve) and neglecting the self-focusing (dashed curve). This plot indicates that by neglecting the self-focusing term in Eq. (8), the laser beam diverges during travelling in the plasma medium. However, by considering the self-focusing, laser beam width parameter decreases due to the relativistic effects and ponderomotive force. Later the beam width starts to increase due to the attraction of the electrons with the ions and decreasing of the dielectric constant. As a consequence, the laser beam undergoes an oscillatory focusing/defocusing behavior along the propagation direction.

Figure 2 shows the electron density distribution n_e, *versus* r. As one can notice from the beam width parameter $f = 1$ that is related to unfocused beam, the electrons distributed uniformly along r (solid curve). However, for the focused beams (f is less than one) that are shown by dashed and point curves, one can see for smaller f the electrons distribution become more inhomogeneous and the electrons distributed in region far from the axis due to the ponderomotive force.

One can also investigate the electron density distribution along the propagation direction of the laser beam. Regarding Eq. (3) and substituting the beam width variation (f), one can have an oscillatory distribution of ne and this is completely agrees with the result of self-focusing of the laser beam. This is shown in Figure 3 and as one can see for regions with $n_e(z)/n_0 = 1$, which is related to the uniform distribution of the electron density, the beam width parameter value is $f = 1$ and in the regions with $n_e(z)/n_0 = 0$ that is related to the maximum self-focusing, the beam width parameter is minimum. Figures 1 and 3 are in good agreement with the work of Brandi *et al.* (1993), which is obtained with a different approach.

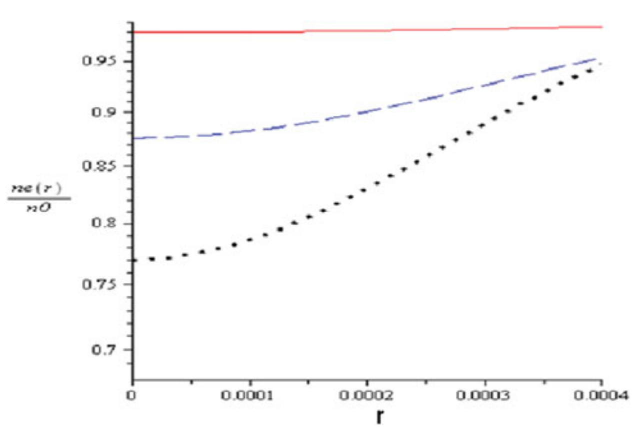

Fig. 2. (Color online) The changes of electron density along r: for $f = 1$(solid curve), $f = 0.6$ (dash curve), $f = 0.5$ (dot curve).

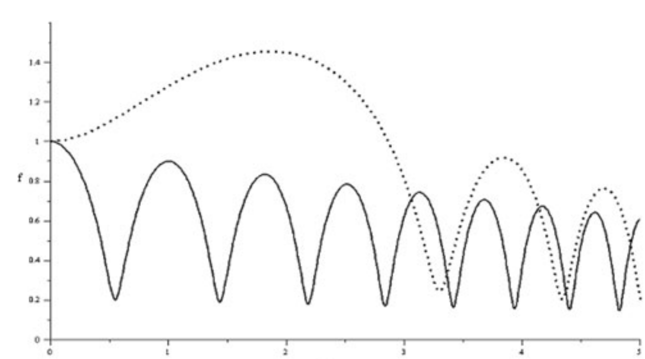

Fig. 4. Dependence of beam width parameter f on distance of propagation ξ in underdense plasma mass for ramp density profile with function as $n_{e0} = n_0 \times \tan(z/d)$ (dot curve) and $n_{e0} = n_0 + n_0 \tan(z/d)$ (solid curve).

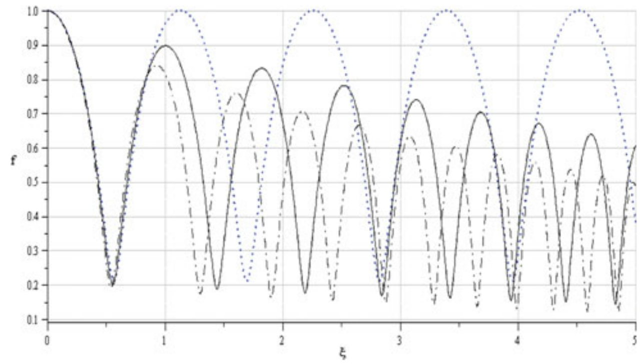

Fig. 5. (Color online) Dependence of the beam width parameter f on distance of propagation ξ in underdense plasma for ramp density profile with function as $n_{e0} = n_0 + n_1\tan(z/d)$, with different n_1 ($n_1 = 0$ (dot curve), $n_1 = n_0$ (solid curve), $n_1 = 2\,n_0$ (dash curve).

THE PROPOSED DENSITY RAMP AND THE RESULTS

To overcome the defocusing of laser beam due to attraction of centralized ions at the axis, Gupta *et al.* (2007*a*) introduced a density ramp varying along laser propagation (z) in the form of $n_0 + \tan(z/d)$. Where n_0 is the electron density at $z = 0$ and d is a constant factor. Regarding dimension correction revised papers are presented and an acceptable form of density ramp is introduced as $n_0 \times \tan(z/d)$ (Gupta *et al.*, 2007*b*; Sadighi-Bonabi *et al.*, 2010*f*, 2010*g*). Introducing the new density profile of $n_{e0} = n_0 + n_0\tan(z/d)$, one can investigate the beam width variation for mentioned profile.

In Figure 4, the beam width parameter variation, for two different density ramps are compared at the same conditions. A considerable decrease of beam width parameter for introduced density ramp of $n_{e0} = n_0 + n_0\tan(z/d)$ is obtained in comparison to the earlier profile of $n_{e0} = n_0 \times n_0\tan(z/d)$. By using here introduced density ramp, the laser beam width parameter decreased up to 20% of the initial value. The frequency of oscillation also decreased noticeably.

Self-focusing can produce extremely high laser intensity that can have numerous important applications such as ELI

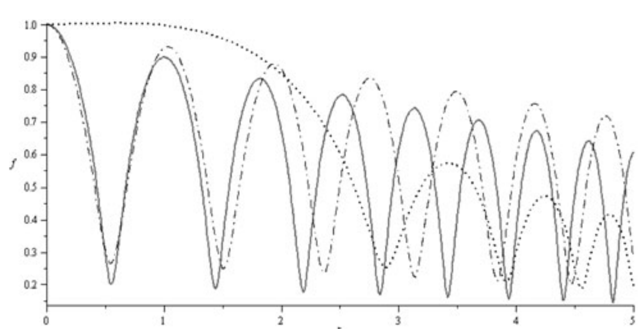

Fig. 6. Comparing self-focusing of different intensities; $I = 10^{19}$ W/cm^2 (dot curve), $I = 10^{18}$ W/cm^2 (solid curve), $I = 10^{19}$ W/cm^2 (dot-dashed curve).

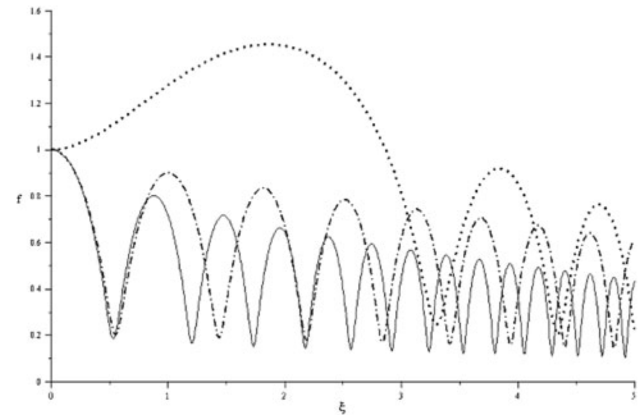

Fig. 7. Dependence of beam width parameter f on distance of propagation ξ in underdense plasma for ramp density profile with function as $n_{e0} = n_0 \times \tan(z/d)$ (dot-dash curve), $n_{e0} = n_0 + n_0\tan(z/d)$ (dash curve) and $n_{e0} = n_0 + n_1\tan(z/d)$ (solid curve).

(www.extreme-light-infrastructure.eu/eli-home.php), ion acceleration in fusion applications (Ting *et al.*, 1997; Hegelich *et al.*, 2006). The realistic expectation is focusing of high power lasers in dimensions comparable to the laser wavelength. For this purpose, even more useful density ramp is introduced as $n_{e0} = n_0 + n_1\tan(z/d)$. Based on this new ramp profile Figure 5 is produced where self-focusing for different n_1 is plotted.

Simulating the Nd:Glass laser parameters in the intensities of $I = 10^{17}$, $I = 1.2 \times 10^{18}$, $I = 10^{19}$ (W/cm^2), one can see that the best self-focusing, occur at the critical relativistic intensity of $I_{cr} = 1.2 \times 10^{18}$ (W/cm^2). This is shown in Figure 6.

Regarding the optimized laser and plasma parameters and introducing the above mentioned density ramp, beam width parameter of close to 10% of the initial value is obtained and this is shown in Figure 7. In this condition, the laser beam width parameter reduced up to about 10% of its initial beam width parameter and this is equal to about one laser wavelength.

CONCLUSION

In this work, simulation and optimization of the self-focusing of laser beam along the propagation axis is investigated. Focusing of the laser beam up to the laser wavelength by the new density profile is achieved. The effect of different laser intensities is also studied and the best intensity for achieving minimum laser beam width parameter is shown. This achievement can have very important impact in fast ignition processes in which self focusing is very important factor.

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