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Optimizing laser focal-spot size using self-focusing in a cone-guided fast ignition ICF target

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ABSTRACT

This paper presents a scheme for strong self-focusing of a laser beam interacting with a cone-guided fast ignition inertial confinement fusion (ICF) target using cone pre-plasma filling as an optical medium for reducing the laser beam waist. The objective being to reduce the focal spot size at the interior of the tip of the re-entrant cone to that required for efficient coupling to the dense imploded fuel core. This is challenging to achieve in a large laser system using the standard optical components of a chirped-pulse-amplified (CPA) laser-beam chain where the spot sizes produced are often significantly larger than would be desirable for fast ignition. The approach described also makes use of the presence of pre-plasma in the cone. Such pre-plasma filling is difficult to avoid entirely when illuminating a cone with a high energy CPA laser system due to the challenges of reducing laser pre-pulse to below the threshold for plasma production. For deriving the differential equation which governs the progress of the laser beam-width with propagation distance, paraxial theory in a WKB approximation has been used. A simulation is performed assuming strong self-focusing in accordance with the laser parameters and plasma density profile chosen.

1. Introduction

Much recent work on Fast Ignition (FI) [1] for Inertial Confinement Fusion (ICF) [2] has involved the use of capsules in which a re-entrant gold cone has been imbedded [3]. As in the original scheme described in Ref. 1 the re-entrant cone-guided FI scheme employs a laser pulse with power on the order of 10 PW and energy of around 100 kJ to heat a region of approximately $1000\times$ compressed equimolar deuterium-tritium (DT) fuel, that satisfies the ρr criterion for ignition, to the multi-keV temperatures required for alpha particle bootstrapping and subsequent propagating burn. Here, the igniter laser pulse is incident on the interior of the gold cone, which is embedded in the capsule such that the cone tip is directed toward, and located within approximately 100 μm of, the assembled dense fuel core. The object of this cone interface being to avoid the requirement that either the igniter pulse, or a less intense 'hole boring' pulse, first channel through some few millimeters of plasma such as would ordinarily surround the core formed from the uniform spherical implosion of a fuel shell.

The cone-guided fast ignition concept initially showed some promise [4] and these early promising results led to the commencement of the FIREX project in Japan [5], and also formed part of the rationale for adding high energy short pulse beams to Omega and NIF [6, 7]. However, over the past two decades physicists have become increasingly aware of a number of difficulties with the cone-guided fast ignition concept. These difficulties are all related to the challenge of efficiently coupling the energy of the high energy short-pulse laser to the dense imploded fuel core [8]. Essentially there are three main components to this problem: 1) poor collimation of the beam of hot particles (usually envisaged to be electrons) from their point of origin to the dense fuel, 2) the source of the hot particles being too distant from the dense fuel to enable adequate coupling given that the hot particle beam is divergent, and 3) the hot particles having too long a mean free path in the dense fuel. This final point is a problem because, in order for inertially confined fusion to offer the potential of achieving high gain, ignition must necessarily proceed from a compact hotspot which represents only a small fraction of the total fuel mass. The bulk of the fuel must be heated to ignition temperatures by the propagating thermonuclear burn wave. Heating a large fraction of the compressed fuel up to ignition temperatures using the driver nullifies the possibility of achieving significant gain even if ignition is achieved. For electron fast ignition, this difficulty manifests itself in the form of the fast ignition "Catch 22", which may be stated as follows: allowing for other coupling inefficiencies, in order to deposit sufficient energy in the hotspot for it to ignite, prior to it hydrodynamically disassembling, the laser intensity has to be so high that the hot electron temperature (T_{hot}) produced by the interaction of the igniter pulse with the plasma is too high to form a compact hotspot. If the hotspot is larger than is desirable, the energy requirements for ignition are increased, and so therefore the required intensity becomes even larger. This in turn increases T_{hot} even more, and so on and so forth until one ends up with an unfeasibly large short pulse laser heating up the entirety of the fuel; a situation which, as mentioned, can never result in high gain. Another issue posed by the cone-guided scheme is that of the disturbance of the symmetry of the implosion by the presence of the cone. This

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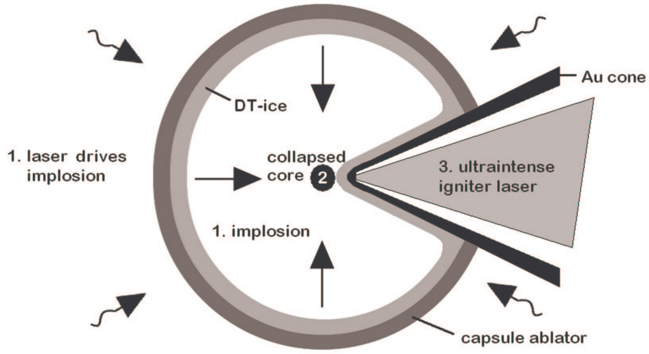


Figure 1: Schematic representation of the cone-guided fast ignition scheme

has recently caused a reconsideration of super-penetration schemes in which the route to the fuel is provided not by a cone but by a laser-produced plasma channel [9].

A further difficulty may also be added to the above list, which is more of a technological challenge on the laser side than a target-physics issue. The first generation of high-energy short-pulse lasers suffered from two difficulties: excessive prepulse and the challenge of producing a near diffraction-limited focal spot. The first of these issues has been quite effectively addressed over the past 15 years, with available laser contrasts increasing from around 10^6 to close on 10^{10}, however the second is more challenging. Omega EP for instance, which is a large, state-of-the-art multi-beam high energy short-pulse laser system, constrains about 80 % of its energy within a 40-50 μm diameter focal spot. Impressive though this is, it is far from optimal if one wishes to efficiently deposit energy in a hotspot of less than 10 μm diameter. This difficulty is related to the scale of such lasers, which have beam-paths hundreds of metres in length. It should be noted also that Omega EP uses deformable mirrors and other advanced technologies to minimise the focal spot diameter [10]. From a fast ignition standpoint, what is critical is the fast electron beam width at the dense fuel. This may be minimized by reducing the source size and the divergence of the electron beam from the interaction region to the dense fuel. Much work has been performed to attempt to minimise the divergence of the hot electron beam, for instance the use of a magnetic switchyard [11] or one of a range of double pulse approaches that use the magnetic field generated by a prior laser-plasma interaction to guide a subsequent high-intensity pulse [12, 13, 14]. Other studies have shown that using a particularly high-contrast laser pulse may enhance self-collimation [15, 16]. It is not clear as yet however which of these approaches will work effectively in a full-scale fast ignition target. Experiments to date have tended to use comparatively short pulse lengths and much lower energies, where both the hydrodynamic and magnetic field evolution during the main pulse is less pronounced than would be the case for the $\sim$ 100 kJ, $\sim$ 10ps laser pulses required for fast ignition.

Here we consider whether target physics might assist in reducing the hot electron source size by further focusing down the incident beam within the re-entrant cone. It must be stressed however that in doing this the intensities produced must still be limited so as not to produce an excessively high T_{hot}. There are several routes that one might consider to achieving this in a general case (without worrying too much about the specific requirements of fast ignition). One might propose a target-level focusing scheme that is based on target geometry, such as that described in [17], or one might rely upon the tendency of a high-intensity laser to self-focus in a low-density plasma background. This latter approach is that which is considered here, i.e. the possibility of using an ambient plasma to self-focus a laser, which would otherwise have a focused intensity of around 10^{18} to 10^{19} W/cm^2, up to intensities suitable for fast ignition (10^{19} W/cm^2 +) whilst at the same time reducing the focal spot diameter so as to optimise coupling to a compact hotspot. Clearly self-focusing requires the presence of some ambient plasma medium in order to operate, however such a medium tends to be present in the case of cone-guided fast ignition anyway. Whilst, as noted, laser contrast levels have been greatly improved since the advent of high-energy short-pulse laser technology, it is still challenging to entirely avoid the formation of some pre-plasma within the cone. This scheme therefore also has the benefit of making use of this pre-plasma, indeed it may be argued that what is proposed here does not actually represent any kind of evolution of the existing cone-guided fast ignition target - it merely emphasizes the potential utility of what is often considered to be a problem (pre-plasma) in terms of it providing a possible solution for another issue (the over-large focal spots of high energy lasers). There also exist more substantial modifications to the established fast ignition schemes, such as the double-cone ignition scheme proposed by Zhang *et al.* [18] in which the use of a magnetic field generated by a nanosecond laser is evoked to guide the fast electrons toward their target and the compression geometry is also substantially modified.

The current work may be seen as an advancement upon a number of related analytical and simulation-based studies, using similar techniques, that have been published previously. Hafizi *et al.* [19] proposed a theoretical model for the propagation of an intense laser beam in a plasma, considering pondermotive and relativistic effects. Lui and Tripathi [20] presented observations of the effects of a self-generated azimuthal magnetic field upon the relativistic self-focusing of an intense laser beam in a plasma. Gupta *et al.* [21] considered the case of an upward plasma-density ramp in underdense plasma, and concluded that introducing such an upward plasma-density ramp allows for the achievement of the minimum spot size via self-focusing. In the absence of a density ramp, diffraction tends to dominate and the laser beam becomes defocussed. Kant *et al.* [22] observed self-focusing of a Hermite Gaussian laser beam in the presence of an upward plasma density ramp which also led to stronger self-focusing. Saedajali *et al.* [23], studied the interaction of a self-focused laser beam with a plasma-loaded cone in the context of cone-guided fast ignition. Here we take the obvious further step of introducing an upward plasma density ramp into the cone in order to obtain stronger self-focusing. This is also of interest since an upward plasma density ramp is inevitably created by the interaction of the laser pre-pulse with the interior of the cone, though of course given that this is a largely analytical study, the density profile is idealised. Self-focusing has also been invoked in fast-ignition related experiments, often in the cone-less variant of the technique, as a phenomenon that may assist in conveying the energy of the igniter beam to the dense fuel [24, 25]. Another well-known component of high-intensity laser-plasma interactions, closely related to whole-beam self-focusing, is beam filamentation. It has been previously shown that in a collisional plasma with finite thermal conduction, the extent of filamentation is significantly less than that of self-focusing, hence it is not considered further here [26]."

It should be noted that with a reduced-physics model, such as that which is employed here, it is not possible to make any firm statements as to the overall effect of pre-plasma in a cone-guided fast ignition scenario. Indeed experimental studies have illustrated how the presence of preplasma can significantly inhibit coupling of laser energy to the cone tip [27] albeit at a greatly reduced energy scale. The present study serves only to illustrate one aspect of the physics of the interaction, and suggest a way in which it may be beneficial. Also, as stated, it is reasonable to expect that some preplasma may be present in a full-scale fast ignition experiment, and so it is important to examine the many different ways in which its presence may affect the interaction. With the model employed here, only one aspect of the interaction can be interrogated, and this should be borne in mind when considering the results presented.

2. Theoretical Considerations

Let us consider a Gaussian laser beam propagating along the z-axis in a plasma. In the presence of a collisionless plasma, the propagation of a Gaussian laser beam is characterized by

$$\varepsilon = \varepsilon_0 + \phi(< EE^* >), \tag{1}$$

with $\omega_p^2 = 4\pi n(\xi)e^2/m$, $\varepsilon_0 = 1 - \omega_p^2/\omega^2$. Here, the frequency of laser used is given by ω, the linear and non-linear parts of dielectric constants are represented by ε_0 and ϕ respectively, ω_p^2 is the plasma frequency, electron charge is given by e and electron mass is given by m. The upward plasma density ramp density ramp profile is modulated as

$$n(\xi) = n_0 \tan\left(\frac{\xi}{d}\right), \tag{2}$$

where the equilibrium electron density is denoted as n_0, $\xi = z/r_d$ is the normalized propagation distance and d is a dimensionless adjustable parameter which specifies the gradient of the slope. The extent of the plasma that will be employed here ($\sim$ 100 microns) is in keeping with that to be expected based upon previous studies and the expected speed of sound and time duration relevant to the prepulse interaction in a fast ignition target. The non-linearity in the dielectric constant is mainly due to the pondermotive force and the non-linear part of the dielectric constant is given by

$$\phi(EE^*) = \frac{\omega_p^2}{\omega^2}\left[1 - \exp\left(-\frac{3m\alpha EE^*}{4M}\right)\right], \tag{3}$$

with $\alpha = e^2M/6m^2\omega^2k_bT_0$, where M is the mass of the scatterer in the plasma, k_b is the Boltzmann constant and T_0 is the equilibrium plasma temperature.

3. Relativistic Self-focusing

Consider a high intensity laser beam propagating in plasma with an upward density ramp through a cone. The wave equation governing the propagation of a laser beam in the plasma is:

$$\nabla^2 E + \frac{\omega^2}{c^2}\varepsilon E = 0. \tag{4}$$

The above equation is solved by using the WKB approximation. The solution of the wave equation is,

$$E = A(x, y, z)\exp[i(\omega t - kz)], \tag{5}$$

where

$$k = \sqrt{1 - \frac{\omega_{p0}^2}{\gamma\omega^2}\tan\left(\frac{\xi}{d}\right)}\left(\frac{\omega}{c}\right) \tag{6}$$

and the plasma frequency ω_p^2 is given by,

$$\omega_p^2 = \frac{\omega_{p0}^2}{\gamma}\tan\left(\frac{\xi}{d}\right). \tag{7}$$

Differentiating equation (4) twice with respect to r and z we get,

$$\frac{\partial E}{\partial r} = \exp[i(\omega t - kz)]\frac{\partial}{\partial r}A(r, z), \tag{8}$$

$$\frac{\partial^2 E}{\partial r^2} = \frac{\partial^2}{\partial r^2}(A(r, z)\exp[i(\omega t - kz)]), \tag{9}$$

$$\frac{\partial E}{\partial z} = \frac{\partial}{\partial z}(A(r, z)\exp[i(\omega t - kz)]). \tag{10}$$

Substituting $\tan\left(\frac{\xi}{d}\right) = \tan\left(\frac{z}{dR_d}\right)$ where, R_d denotes the diffraction length, into equation (9) we get,

$$\frac{\partial E}{\partial z} = \exp[i(\omega t - kz)]\left[\frac{\partial A}{\partial z}\right] + \frac{Ai\omega}{c}\sqrt{1 - \frac{\omega_{p0}^2}{\gamma\omega^2}\tan\left(\frac{z}{dR_d}\right)} + \frac{\frac{i\omega z}{2cdR_d}\frac{\omega_{po}^2}{\gamma\omega^2}zA\sec^2\left(\frac{z}{dR_d}\right)}{\sqrt{1 - \frac{\omega_{po}^2}{\gamma\omega^2}\tan\left(\frac{z}{dR_d}\right)}}. \tag{11}$$

Similarly,

$$\frac{\partial^2 E}{\partial z^2} = -\frac{\omega^2 A}{c^2} \exp[i(\omega t - kz)] \left[\frac{\omega_{p0}^4 z^2 sec^4\left(\frac{z}{dR_d}\right)}{\gamma^2\omega^4 d^2 R_d^2 \left[1 - \frac{\omega_{p0}^2}{\omega^2}\tan\left(\frac{z}{dR_d}\right)\right]} \right] + \left[1 - \frac{\omega_{p0}^2}{\gamma\omega^2}\tan\left(\frac{z}{dR_d}\right)\right]. \quad (12)$$

Writing the wave equation in cylindrical coordinates and substituting in equations (8), (9), (10) and (11) we get,

$$\frac{i\omega}{c}\left[2\sqrt{1-\frac{\omega_{p0}^2}{\gamma\omega^2}\tan\left(\frac{z}{dR_d}\right)} - \frac{\frac{\omega_{p0}^2}{\gamma\omega^2} z \sec^2\left(\frac{z}{dR_d}\right)}{dR_d\sqrt{1-\frac{\omega_{p0}^2}{\gamma\omega^2}\tan\left(\frac{z}{dR_d}\right)}}\right]\frac{\partial A}{\partial z} - \frac{\frac{\omega_{p0}^2}{\gamma\omega^2} A \sec^2\left(\frac{z}{dR_d}\right)}{dR_d\sqrt{1-\frac{\omega_{p0}^2}{\gamma\omega^2}\tan\left(\frac{z}{dR_d}\right)}}\left[1+\frac{A}{dR_d}\left(\tan\left(\frac{z}{dR_d}\right) + \frac{\frac{\omega_{p0}^2}{\gamma\omega^2} Az \sec^2\left(\frac{z}{dR_d}\right)}{4\left(1-\frac{\omega_{p0}^2}{\gamma\omega^2}\tan\left(\frac{z}{dR_d}\right)\right)}\right)\right] \quad (13)$$

Now,

$$A(r,z) = A_0(r,z)\exp[-ikS(r,z)]. \quad (14)$$

In order to solve equation (12), we differentiate equation (13) and substitute in equation (12). Considering only the real part of the obtained solution,

$$\frac{c^2}{\omega^2 A_0}\left(\frac{\partial^2 A_0}{\partial r^2} + \frac{1}{r}\frac{\partial A_0}{\partial r}\right) + \phi(A_0^2)$$
$$= \left[\left(2\left(1-\frac{\omega_{p0}^2}{\gamma\omega^2}\tan\left(\frac{z}{d_R d}\right)\right)\right) - \frac{\omega_{p0}^2}{\gamma\omega^2}\frac{z\sec^2\frac{z}{dR_d}}{dR_d}\right]\frac{\partial S}{\partial z}$$
$$+ \left[1-\frac{\omega_{p0}^2}{\gamma\omega^2}\tan\left(\frac{z}{dR_d}\right)\right]\left(\frac{\partial S}{\partial r}\right)^2$$
$$- \frac{\omega_{p0}^2}{dR_d\gamma\omega^2}\sec^2\left(\frac{z}{dR_d}\right)$$
$$\times \left[S + z - \frac{\omega_{p0}^2}{\gamma\omega_2^2}\frac{z}{2dR_d}\sec^2\frac{z}{dR_d}\frac{(S-z)/2}{1-\frac{\omega_{p0}^2}{\gamma\omega^2}\tan\left(\frac{z}{d_R d}\right)}\right] \quad (15)$$

In a paraxial approximation, the relation between amplitude, A_0 and S, and the curvature of the wavefront of the beam are given as:

$$S(r,z) = \frac{r^2}{2}\frac{1}{f(z)}\frac{\partial f(z)}{\partial z} + \phi_0(z), \quad (16)$$

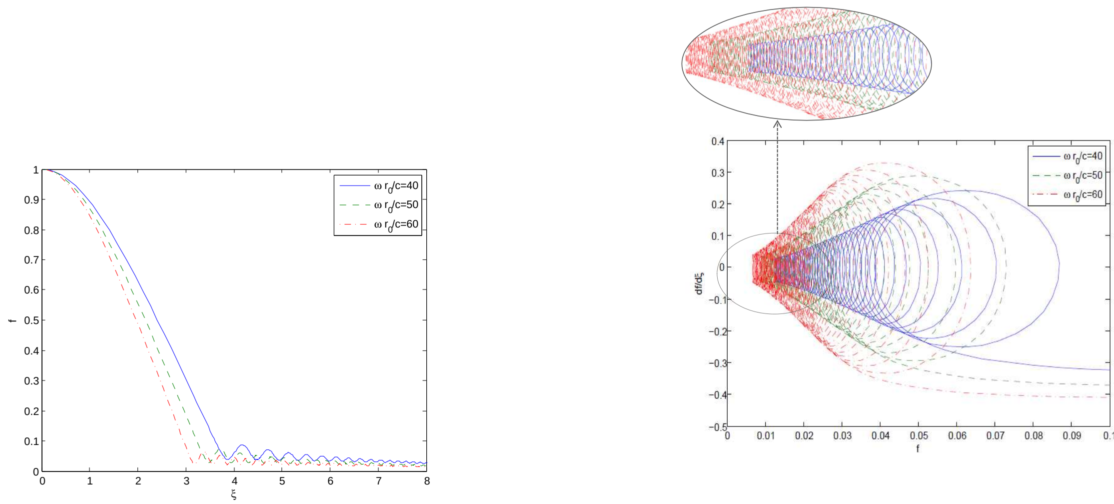
$$A_0(r,z) = \frac{A_{00}}{f(z)}\exp\left(\frac{-r^2}{f^2(z)r_0^2}\right). \quad (17)$$

where A_{00} is the initial magnitude of laser beam at $z = 0$, f is the dimensionless beam-width parameter and r_0 is the initial beam-width radius. Substituting equation (15) and (16) into (14) and taking coeficients of r^2 using the paraxial approximation, and using the dimensionless parameters, $\alpha = \omega_{p0}^2/\omega$ and $\beta = \omega r_0/c$ and $x = \alpha A_{00}^2$, the following equation for the beam-width parameter is deduced,

$$\frac{d^2 f}{d\xi^2} = \left[\frac{1}{\frac{\alpha^2\xi}{2d}\sec^2\left(\frac{\xi}{d}\right) + \left(1-\alpha^2\tan\left(\frac{\xi}{d}\right)\right)}\right] \left[\frac{1}{f(z)}\left[2\left(1-\alpha^2\tan\left(\frac{\xi}{d}\right)\right) + \alpha^2\xi\right]\right]\left(\frac{df}{d\xi}\right)^2 + \left(1-\alpha^2\tan\left(\frac{\xi}{d}\right)\right)^{\frac{1}{2}} \left(\frac{1}{\beta^2 f^3(\xi)} - \frac{x\alpha^2\beta\tan\left(\frac{\xi}{d}\right)}{2f(\xi)}\right)\left(1+\frac{x}{2f^2(\xi)}\right)^{\frac{-3}{2}} - \left(\frac{\alpha^2\beta}{2d}\sec^2\left(\frac{\xi}{d}\right)\right)\left(1-\frac{\alpha^2\xi}{2d}\sec^2\left(\frac{\xi}{d}\right)\frac{1}{1-\alpha^2\tan\left(\frac{\xi}{d}\right)}\right) \left(1-\alpha^2\tan\left(\frac{\xi}{d}\right)\right)^{\frac{1}{2}}. \quad (18)$$

4. Results

In order to solve the equation of the beam width parameter numerically, we have performed simulations for the following parameters, $\omega = 1.778 \times 10^{14}$ rad/sec and $r_0 = 253\mu m$. The initial laser intensity $I_0 = 10^{19} W/cm^2$ and the initial temperature $T_0 = 10^5 K$. Figure 2(a) shows variation of beam width parameter with propagation distance for values of $\omega r_0/c$ = 40, 50 and 60, keeping $\omega_{p0}/\omega = 0.3$ and d = 8. It is found that initially its beam width parameter decreases sequentially and maintains a small spot size as it propagates. Due to the Gaussian intensity side view of the laser beam, the relativistic mass of the plasma electrons is highest at the center of the wave front and is lowest in its wings. Hence, the central portion of the wave front experiences a higher refractive index than that which is off-axis.



(a) (b)

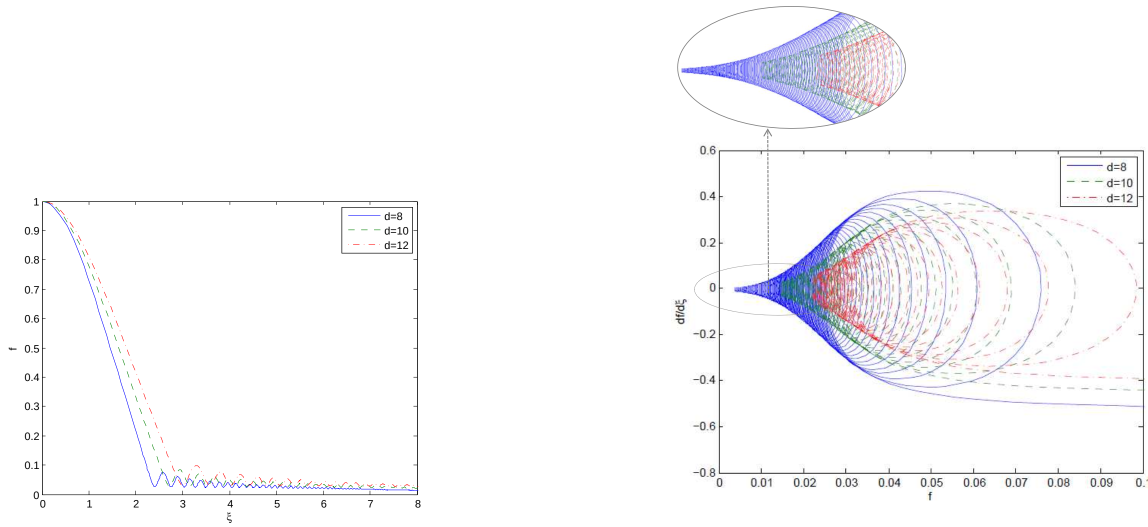
Figure 2: In this figure (a) Variation of beam width parameter with normalised propagation distance and (b)Phase space plot for self-focused Gaussian laser beam, for $\omega r_0/c$ = 40, 50 and 60 at ω_{p0}/ω = 0.3, d=8 is shown

This results in bending of the wave-front and self-focusing of the laser. As the beam propagates through the plasma, it maintains its reduced spot size up to several Rayleigh lengths. It is also observed that after every focal spot the maxima and minima of the spot size of the laser beam shift downwards. This observation is in agreement with 3D PIC simulation results described by Pukhov and Meyer-ter Vehn in [28]. Similarly, figure 3(a) shows the variation of beam-width parameter with propagation distance for values of d = 8, 10 and 12 with $\omega_{p0}/\omega = 0.3$ and $\omega r_0/c = 40$ and figure 4(a) shows the variation of the beam-width parameter with propagation distance for values $\omega_{p0}/\omega = 0.3$, 0.4, 0.5, with $\omega r_0/c = 40$ and d = 8. It is clear that as the laser spot size increases, the repetition of the oscillations grows faster and hence self-focusing becomes stronger and occurs at earlier values of f. The beam is also observed to remain converged for a greater propagation distance.

Figures 2(b), 3(b) and 4(b) are the phase-space plots demonstrating the propagation dynamics of the laser beam. The trajectories obtained are spirally phased which indicates the internal oscillations of the laser beam. These oscillations are rich in different frequencies. In these figures, it can be clearly seen that for smaller values of f, these spiral lines becomes denser, leading to stronger self-focusing. In figure 2(b) self-focusing occurs faster for a larger beam-width parameter. In figure 3(b) at d = 8, a signficant increase in the strength of the self-focusing is apparent, and also this self-focusing has occurred faster. Figure 4(b) shows the presence of denser plasma leads to stronger self-focusing.

5. Conclusions

This study presents an investigation into strong self-focusing of a Gaussian laser beam in the presence of an upward plasma density ramp in a plasma-loaded cone which may be considered in the context of cone-guided fast ignition or other applications where it is advantageous to reduce focal spot size and/or increase laser intensity (for instance in imaging applications, such as those discussed in reference 11). The field distribution of the laser beam is expressed in terms of the beam-width parameter. This setup reduces the defocusing of the laser beam. Hence, the laser beam remains focused to a small spot size up to several Rayleigh lengths which is essential for consistent performance in an extended plasma formed by the interaction of a laser prepulse. The simulation results show that the plasma frequency increases and the self-focusing occurs faster in such a scenario than in a uniform density plasma. Clearly these are the results of a reduced model of laser-plasma interaction, and as such substantial further investigation would be required to clearly establish the importance and utility of this behaviour to cone-



(a) (b)

Figure 3: In this figure (a) Variation of beam width parameter with normalised propagation distance and (b) Phase space plot for self-focused Gaussian laser beam, for d = 8, 10 and 12 at $\omega r_0/c$= 40 andω_{p0}/ω = 0.3 is shown.

guided fast ignition. The heating beam in fast ignition is necessarily rather long, ~ 10 ps, and on such a time-scale a model which properly accounts for the evolution and hydrodynamic motion of the plasma within the cone is called for. Furthermore, the reader is reminded that the presence of preplasma has been shown to have a negative influence on coupling in experimental studies at reduced scale, and that here we consider only one aspect of the laser-plasma interaction.

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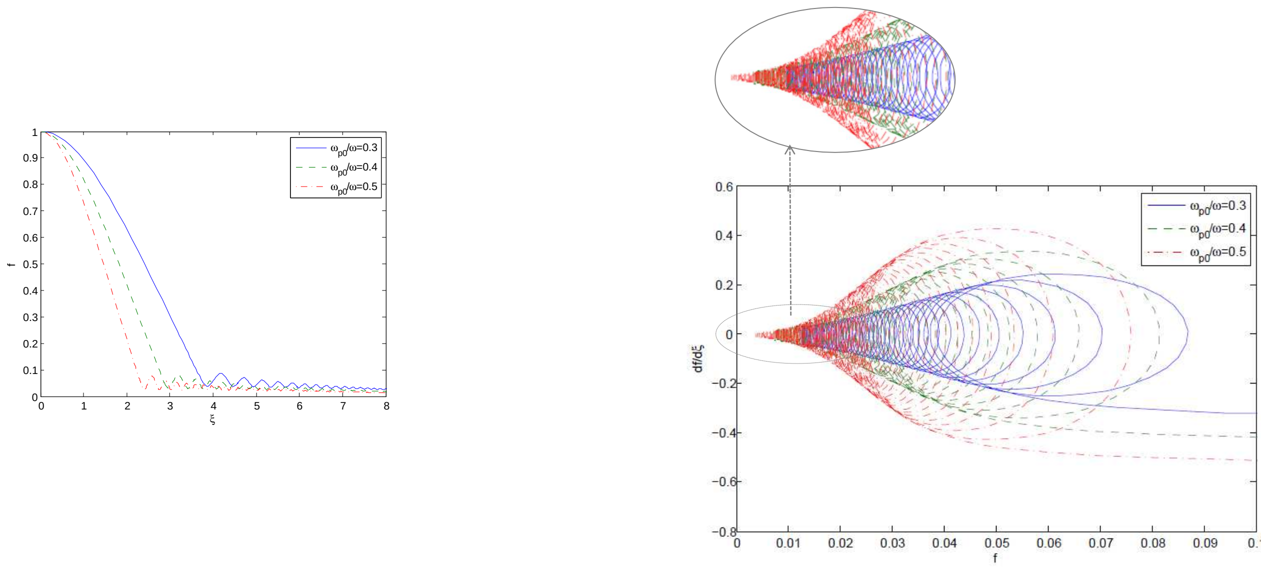

(a) (b)

Figure 4: In this figure (a) Variation of beam width parameter with normalised propagation distance and (b) Phase space plot for self-focused Gaussian laser beam, for different values of ω_{p0}/ω = 0.3, 0.4 and 0.5 at $\omega r_0/c$= 40 and d=8 is shown.

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