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The role of compound lens in optimizing the irradiation uniformity in longitudinal pumping laser*

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In order to optimize the axial irradiation uniformity of a laser in plasma, this paper investigates the role played by the compound lens using a ray-tracing method. Obtained results show that the adoption of the compound lens is capable of increasing the axial line-focus length. Meanwhile, after the energy attenuation in the plasma has been considered, moderating the optical parameter of the compound lens to obtain the corresponding energy output to compensate for the attenuation optimizes the irradiation uniformity along the focal line.

Keywords: longitudinal pump, compound lens, ray-tracing, axial line-focus
PACC: 4215D, 4255V, 4278

1. Introduction

Since Nickels *et al*[1] in 1997 achieved experimentally high-gain x-ray laser in the transient collisional excitation scheme with only several joules, the gain coefficient of the transient Ni-like and Ne-like x-ray laser has been increased to 35cm^{-1} experimentally.[2] However, as the short lifetime confinement of the transient population inversion resulted from the transient excitation mechanism, the gain length under the condition of transversely pumping could not be too long. As a result, this limits the total output intensity of the x-ray laser.[3,4] Therefore, developing a travelling-wave pumping method to overcome these difficulties becomes a resolving means to pursue. On the basis of the concept of the travelling-wave pumping, Li *et al*[5] proposed the experimental approach of longitudinal pumping, and scientists have made some related attempts and achieved certain progress.[6,7] In 2002, Ozaki *et al*[8] attained a huge development with this approach experimentally, with high-intensity 475fs-duration laser pulse to pump 2mm-Mo slab target plasma longitudinally to achieve a directive 18.9nm x-ray laser output. This opens a way for realizing 'table-top' x-ray lasers.

Although the longitudinal pumping scheme for lasers achieves some success experimentally, the gain length of the x-ray lasers is still short with the laser intensity rapidly decreasing due to the plasma absorption and the refraction of the plasma density gradient. Therefore, how to optimize the irradiation uniformity along the focal line turns out to be the key factor in enhancing the longitudinal-pumping x-ray laser output. Early in 1994, to optimize the laser irradiation uniformity, Stevenson *et al*[9] carried out a research with a binary-phase zone plate to attain irradiation uniformity, based on the phase modulation of a parallel light by using a phase plate to attain multi-point focusing; this resulted in a nice modulation of the foci station and the focusing intensity. Subsequently, Bett *et al*[10] investigated the influence of the double-phase zone plate on the laser irradiation uniformity. But the application of the zone plate to optimize uniformity is arbitrary and the intensity of each focus is hard to control due to some productive characteristics when the binary-phase zone plate is machined.

In this paper, the scheme of compound lens used to attain the approximately uniform irradiation is proposed and studied to realize the control on the distribution of luminous intensity. A ray-tracing code to

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investigate the characteristics of the compound lens is developed. In Section 2, the model for the longitudinal pumping x-ray laser scheme is described. In Section 3, the equation of the compound lens is established. In Section 4, the result is analysed, and the work is summarized in Section 5.

2. Model and fundamental equations

The experimental scheme of the longitudinal pumping slab target x-ray laser is shown in Fig.1. Firstly, the transversely pumping laser pulse acts on the slab target as a pre-pulse, which produces a Ni-like (Ne-like) pre-plasma at an appropriate temperature, density and large abundance. Then the main pulse longitudinally pumps the plasma and produces the population inversion. As the direction of travelling wave amplification is consistent with that of longitudinal pumping of the x-ray laser, the synchronization of the pump and transient population inversion is required to increase the gain length of the x-ray laser. In this paper, the longitudinal pumping laser experiment is designed with a group of lenses with different radii of curvature. Considering the influence of the absorption of the longitudinal pumping laser along the focal line, we put emphasis on the characteristics of the axial line-focus of the compound lens.

As far as an ordinary plane–convex lens in producing the axial line-focus along the optical axis is concerned, the focal length is expressed as

$$f = \frac{r_1}{n-1}, \tag{1}$$

where r is the radius of curvature of each sub-sphere, n is the refractive index of the material, and f is the focal length of the plane–convex lens. From formula (1), we see that the focus is proportional to the radius of curvature, and the light intensity at each focus is proportional to the optical flux of each sphere. If lenses with different radii of curvature are composed into a compound lens (see Fig.1), multi-point focusing of pumping laser along the optical axis can be achieved. On the basis of the above assumption and the geometrical law, the compound lens with four different optical parameters is analysed. If a light beam can be divided into four parts and the intensity at each focus can be modulated, the irradiation uniformity of the laser along the axial focal line is capable of being amended to a visible extent.

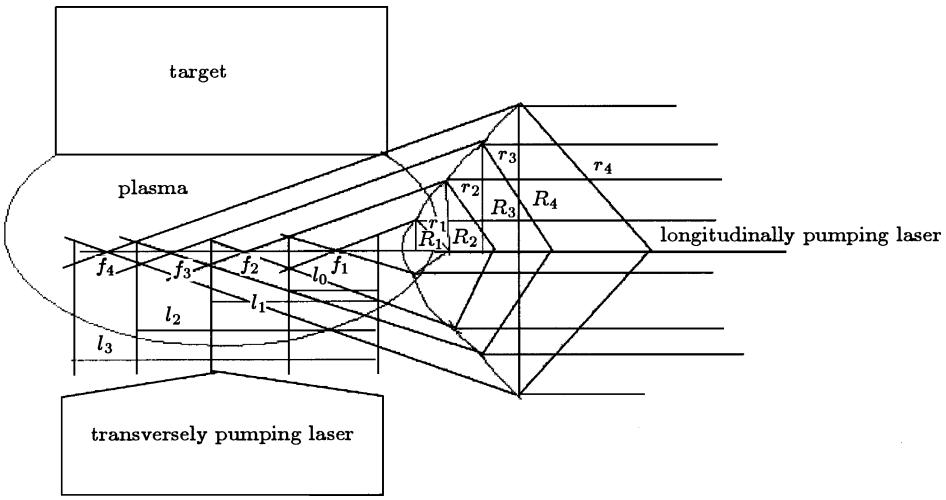


Fig.1. Structures of longitudinal pumping laser with a compound lens. r_1, r_2, r_3, r_4 are radii of the four sub-spheres, R_1, R_2, R_3, R_4 are semi-heights of the four sub-spheres, f_1, f_2, f_3, f_4 are focal lengths of the four sub-spheres, l_0, l_1, l_2, l_3 are the line-focus lengths calculated using one, two, three, and four sub-spheres.

As far as the compound lens is concerned, the radius and the semi-height of each sub-sphere are separate parameters (shown in Fig.1). For the sake of the purposeful research, the distribution of semi-height R determines the focal intensity at each focus, whereas the combination of r and R fully ascertains the structure of compound lens. In this section, on the basis of the law of geometrical lens, the intensity at each fo-

cus of the compound lens in Fig.1 (composed of four lenses with different radii of curvature) is expressed as

$$\begin{aligned} e_1 &= E_0\pi R_1^2, \\ e_2 &= E_0\pi(R_2^2 - R_1^2), \\ e_3 &= E_0\pi(R_3^2 - R_2^2), \\ e_4 &= E_0\pi(R_4^2 - R_3^2), \end{aligned} \tag{2}$$

where R_1, R_2, R_3, R_4 stand for the four semi-heights of the sub-spheres. In order to obtain an approximate uniform line-focus, a confinement of the diffusion diameter is necessary. Assuming that the maximum diameter of the dispersed spot is d, in conjunction with the corresponding relationship of the triangle, we obtain the following formulae:

$$\begin{aligned} \mathrm{tg}\,\alpha_1 &= (n-1)\sin\theta_1 = (n-1)\frac{R_1}{r_1}, \\ \mathrm{tg}\,\alpha_2 &= (n-1)\sin\theta_2 = (n-1)\frac{R_2}{r_2}, \\ \mathrm{tg}\,\alpha_3 &= (n-1)\sin\theta_3 = (n-1)\frac{R_3}{r_3}, \\ \mathrm{tg}\,\alpha_4 &= (n-1)\sin\theta_4 = (n-1)\frac{R_4}{r_4}, \end{aligned} \tag{3}$$

where α_n stands for the blur angle of the parallel light after being focused, and n is the refractive index of the material. Then the diffusion condition takes the form

$$\begin{aligned} \frac{d}{2}\mathrm{ctg}\alpha_2 + \frac{d}{2}\mathrm{ctg}\alpha_1 &< \frac{r_2 - r_1}{n-1}, \\ \frac{d}{2}(\mathrm{ctg}\alpha_3 + \mathrm{ctg}\alpha_2) &< \frac{r_3 - r_2}{n-1}, \\ \frac{d}{2}(\mathrm{ctg}\alpha_4 + \mathrm{ctg}\alpha_3) &< \frac{r_3 - r_2}{n-1}. \end{aligned} \tag{4}$$

The above formulae provide a confined condition for the design of our optical system; only designs conforming to this condition are feasible. On the other hand, the power output of the foci along the axial line-focus is expressed as $e_4 : e_3 : e_2 : e_1 = D_3 : D_2 : D_1 : 1$. In combination with formula (2), the following expression can be obtained:

$$\begin{aligned} R_2 &= \sqrt{D_1 + 1}R_1, \\ R_3 &= \sqrt{D_2 + D_1 + 1}R_1, \\ R_4 &= \sqrt{D_3 + D_2 + D_1 + 1}R_1. \end{aligned} \tag{5}$$

Evidently consideration of the dispersed spot is another key factor of the experiment design. After the corresponding relationship between the radii (r_1, r_2, r_3, r_4) is calculated with the energy distribution at each focus given, only the radius group that satisfies the following formulae is suitable (α is the blur angle after focusing):

$$\begin{aligned} \frac{r_1}{R_1} + \frac{r_2}{R_2} &< \frac{2(r_2 - r_1)}{d}; \\ \frac{r_2}{R_2} + \frac{r_3}{R_3} &< \frac{2(r_3 - r_2)}{d}; \\ \frac{r_3}{R_3} + \frac{r_4}{R_4} &< \frac{2(r_4 - r_3)}{d}. \end{aligned} \tag{6}$$

With the given r_1 and R_1, in combination with formula (5), the axial line-focus length is expressed as

$$\begin{aligned} l_0 &= \frac{2dr_1}{R_1}, \\ l_1 &= l_0 + \frac{2dr_2}{R_2}, \\ l_2 &= l_1 + \frac{2dr_3}{R_3}, \\ l_3 &= l_2 + \frac{2dr_4}{R_4}, \end{aligned} \tag{7}$$

where l_0 is the line-focus length for single-lens, l_1 is the line-focus length for the double-lens, l_2 is the line-focus length for triple-lens, l_3 is the line-focus length for four lenses, and d is the diffusion diameter.

3. Calculated result and analysis

To test the theoretical result, some applicative programs are designed and the result is described in the corresponding graph.

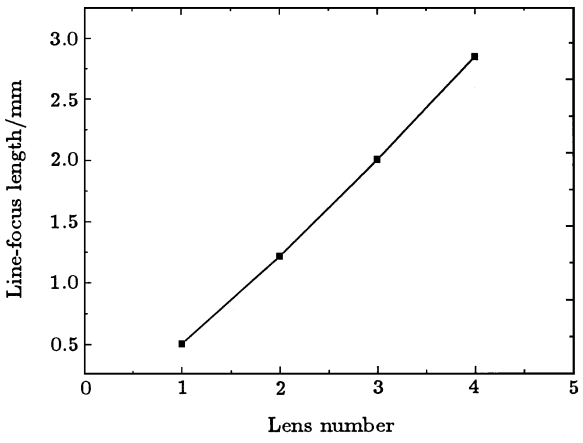


Fig.2. Relation between the line-focus length and the number of lenses. The semi-height of the first sphere is set to be 1mm, that of the outermost sphere is set to be 2mm, and the dispersed spot is set to be 0.02mm.

In order to investigate the influence the number of lenses on the axial line-focus, the semi-height of the outmost sphere of the compound lens is set as 2mm. That is to say, when single sub-lens is used, R_1=2mm; for two sub-lenses, R_2=2mm; for three sub-lenses, R_3=2mm; and for four sub-lenses, R_4=2mm. The

line-focus length with one, two, three and four sub-spheres are calculated using formulae (5) and (7). As seen from Fig.2, the line-focus length increases from 0.5 to 1.21, 2.00, and 2.84 as the number of lenses increases from one to two, three, and four, respectively.

Secondly, the influence of the radius of the first sub-sphere (r_1) on the axial line-focus length is investigated. The semi-height of the fourth sub-sphere is assumed to be 2mm, the diffusion diameter to be 20μm, the line-focus length is calculated using formulae (5) and (7). As seen from Fig.3, the line-focus length l_3 for four sub-spheres varies from 2.84 to 3.40, 4.54, to 5.10mm when r_1 varies from 25, 30, 40, 45, to 50mm, respectively. That is to say, with the increase of the radius r_1, the corresponding line-focus length increases too.

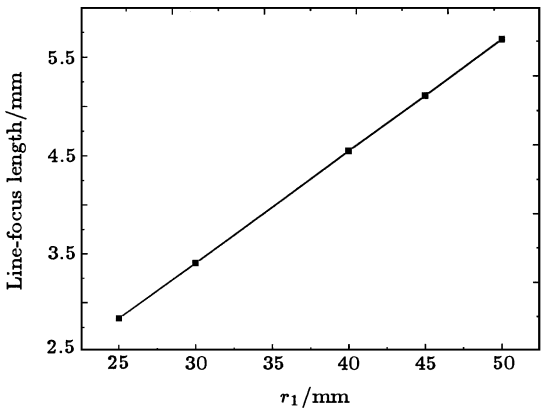


Fig.3. Relation between the line-focus length and the radius of the first sub-sphere. The four focusing points acquires equal energy, the semi-height of the fourth sphere is set to be 2mm, and the dispersed spot diameter is set to be 0.02mm.

Thirdly, the influence of power output percentage on axial line-focus length is calculated, in which r_1 is set to be 50mm, and the diffusion diameter set to be 0.02mm. If R_4 is set to be 20mm, the line-focus length l_3 varies from 4.79 to 3.76, 1.58, 0.56, 1.30, 2.67, and 3.64mm when the power percentage varies from 1000:100:10:1 to 500:50:5:1, 50:10:2:1, 1:1:1:1, 1:2:10:50, 1:5:50:500, and 1:10:100:1000. As seen from Fig.4, when the output percentage is set to be 1:1:1:1, the line-focus length reaches its minimum.

From the above analysis in which is emphasized the possibility of the compound lens to extend the line-focus length, it can be concluded that the use of a compound lens is able to improve the irradiation uniformity, whereas under our practical conditions, in order to obtain the actual line-focus uniformity, it is required that when the foci are away from the zenith of the sphere, the outer sphere distributes more energy per second so as to ascertain the approximately equal distribution of the energy of different sub-sphere along the line-focus after taking into account the absorption of the laser energy, which requires $D_4 > D_3 > D_2 > D_1$.

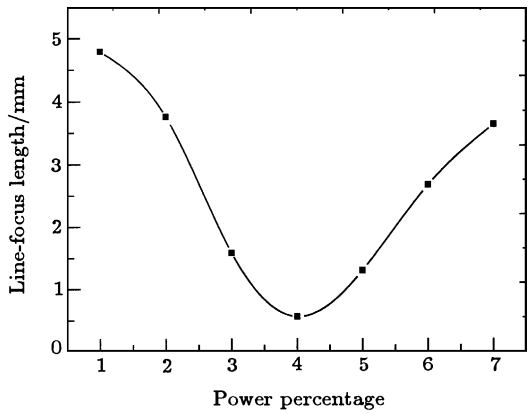


Fig.4. Relation between the line-focus length and the output power percentage. The abscissa expresses output power percentage (1 stands for 1000:100:10:1; 2 stands for 500:50:5:1; 3 stands for 50:10:2:1; 4 stands for 1:1:1:1; 5 stands for 1:2:10:50; 6 stands for 1:5:50:500; 7 stands for 1:10:100:1000). The semi-height of the fourth sphere is set to be 20mm, the radius of the first sphere is set to be 50mm, and the dispersed spot diameter is set to be 0.02mm.

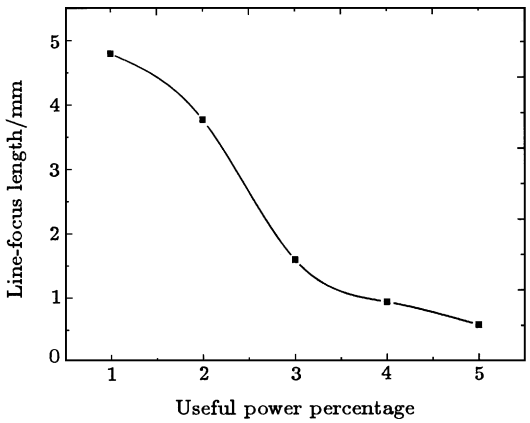


Fig.5. Relation between the line-focus length and the useful output power percentage. The abscissa denotes the useful output power percentage (1 stands for 1000:100:10:1; 2 stands for 500:50:5:1; 3 stands for 50:10:2:1; 4 stands for 10:5:2:1; 5 stands for 1:1:1:1). The semi-height of the fourth sphere is set to be 20mm, the radius of the first sphere is set to be 50mm, and the dispersed spot diameter is set to be 0.02mm.

Now, the influence the percentage of energy distribution on the linear line-focus is studied. If we assume r_1=50mm, R_4= 20mm, d=20μm, then the optical parameters of our compound lens must be adjusted to achieve the different power output percentages so as to

result in the variation of the line-focus length desired. The relation between the output percentage and line-focus length is shown in Fig.5. The line-focus length l_3 varies from 4.79 to 3.76, 1.58, 0.92, and 0.56mm when the power output percentage varies from 1000:100:10:1 to 500:50:5:1, 50:10:2:1, 10:5:2:1, and 1:1:1:1. In a word, the larger the moderated power percentage, the longer the line-focus length.

Secondly, in order to investigate the influence of the radius of the first sub-sphere (r_1) on the line-focus length for a certain energy output percentage, power output percentage is assumed to be 1000:100:10:1, R_1=1mm, when r_1 changes, the line-focus length changes too. In Fig.6, the relation between the radius and the line-focus length for four combined sub-spheres is demonstrated. The line-focus length l_3 varies from 2.04 to 2.45, 2.55, 2.86, and 3.47mm if r_1 varies from 35 to 40, 45, 50, and 60mm. That is, the line-focus length increases with increasing r_1.

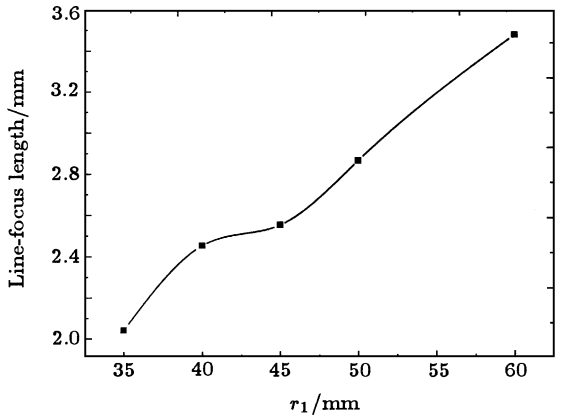


Fig.6. Relation between the line-focus length and the radius of the first sub-sphere. The output power percentage is set to be 1000:100:10:1, the semi-height of the fourth sphere is set to be 32.33mm, and the diameter of the dispersed spot is set to be 0.02mm.

Thirdly, the influence of the semi-height R_1 on the line-focus length with a certain output percentage is studied. Here the energy output percentage is assumed to be 1000:100:10:1, r_1=50mm. In Fig.7, the relation between the radius and the line-focus length for four combined sub-spheres is shown. The line-focus length l_3 varies from 3.57 to 2.84, 2.38, and 2.08mm if R_1 changes from 0.8 to 1.0, 1.2, and 1.4mm. Thus we can conclude that the line-focus length of the compound lens decreases as R_1 increases.

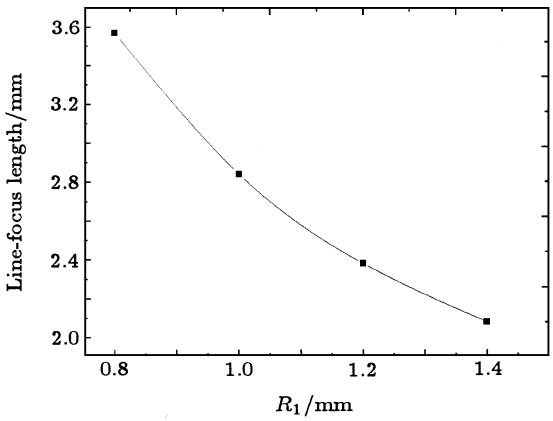


Fig.7. Relation between the line-focus length and the semi-height of the first sub-sphere. The output power percentage is set to be 1000:100:10:1, the radius of the first sphere is set to be 50mm, and the diameter of the dispersed spot is set to be 0.02mm.

4. Conclusion

From the above analysis, we can conclude that (1) The irradiation uniformity in a longitudinal pumping laser is improved by using the compound lens, and (2) the energy attenuation of the laser along the propagation in the plasma is compensated for with the moderation of the structure of the compound lens.

As the composite lens has a flexible design and much bigger modulating atmosphere, the prospects for its research are very bright.

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