Study on focusing performance of the twice reflecting laser focusing system

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Abstract. Laser thrusters characterized by feasible application perspective all possess the twice reflecting laser focusing system. Nonetheless, studies on its focusing performance are imperative for the research of flight route of the thruster and haven’t been developed yet. Under three different focusing design modes, assisted with optical design software ZEMAX which employing Monte Carlo ray tracing, performance of twice reflecting laser focusing system including focusing performance parameters, radiation intensity distribution and the details of ignition region on the focusing plane are studied comparatively, and the studied two main angular aberrations are beam out-coming aberration from laser source and flying aberration from thruster itself. Studies show even slight aberration will result in steep falling focusing performance and strong deviation of beam spot for any focusing design mode, while different aberrations bring in distinctive falling tendencies and the evolutions of ignition region. It strongly demands the directional precision of laser beam, and the attitude control of laser thruster is indispensable. And it’s not recommended that one focusing design mode is superior to another. Which kind of aberration is dominant should be taken into account when choosing focusing mode.

1. Introduction

The advantages of laser thrusters like ASLPE[1] and LITA[2] which possess the twice reflecting laser focusing system are considered as: a) vital separation of optical units and jet nozzle, b) lack of effects of the exhaust jet on the laser beam delivered to the vehicle, c) independence of the vehicle motion control on mutual orientation relative to laser, capturing the thruster vector control. Apparently, all the three points suits ASLPE and LITA to thruster’s demands of feasible application perspective. Consequentially, study on the focusing performance of focusing system is imperative, however, previous works were all carried around once reflecting focusing system incorporating just a parabolic reflector simultaneously playing the role of nozzle which may arouse many defects. Programs using RMT (Ray Tracing Method) in order to explore ray path have been used for focusing performance analysis of parabolic reflector for years[3]–[5], but due to the relative complexity of the twice reflecting focusing system, works on its performance haven’t yet been developed. Meanwhile, different thrusters employing different twice reflecting focusing modes that are classified by geometrical type of reflecting surfaces result in which focusing mode is better and the contrast of their
focusing performance is necessary. Now, with flexible non-sequential ray tracing created by optical design software also providing plentiful reflecting surface types, performance analyses of complex focusing system in high precision become simpler and more practicable.

Based on ZEMAX (a non-sequential Monte Carlo ray tracing program), we present works on focusing performance of twice reflecting laser focusing system under three different focusing modes comparatively. Focusing performance parameters and radiation intensity distributions on focusing plane were computed and analyzed under different angular aberrations.

2. Primary physical model

2.1 Geometry Model of Twice Reflecting Laser Focusing System

Schematic diagram of the twice reflecting focusing system, which is toroidal-symmetric and consists of two reflectors with known shape, is shown in figure 1. Z is the incident direction of laser beam and symmetric axis of the system, while axis X, Y, Z satisfy right-hand rule and plane XOY is defined as focusing plane. The laser beam is directed to the mirror R1, after the reflection of R1 to the mirror R2, then reflected to the O (zero point). \( \alpha \) and \( \beta \) are focusing orientation meaning deviation degree of laser beam relative to the incident direction and focusing convergence angle the degree of beam converging. In common use, according to the different generatrix of the reflecting surfaces, integration modes of R1 and R2 could be paraboloid to hyperboloid, cone to paraboloid and paraboloid to cone, which are marked as focusing mode A, B, C respectively in the following text.

![Figure 1. Schematic diagram of the twice reflecting laser focusing system](image)

Based on the coordinate above, three groups of reflecting surfaces are selected as object and the geometrical details are shown in table1. For the comparability of the three focusing modes, \( \alpha \approx 35^\circ \), \( \beta \approx 6^\circ \) and the radius of focusing system of almost 100mm are specified.

| Focusing mode | Reflecting surfaces | Generatrix equation of reflecting surface | Start point \((z, y)\) | End point \((z, y)\) |
|--------------|---------------------|------------------------------------------|----------------|------------------|
| A R1:paraboloid \( (y-550)^2=-500(z-350) \) | \( (z-225)^2 + (y-550)^2 - z^2 - y^2 = 404.26 \) | \((-255, 0)\) | \((-201.3, 25)\) |
| R2:hyperboloid | | | | |
| B R1:cone \( y=\sqrt{z+180} \) | \( z=-580(y-145) \) | \((-180, 0)\) | \((-162.3, 25)\) |
| R2:paraboloid \( (y-270)^2=-500(z+18) \) | | \((-163.8, 0)\) | \((-138.1, 25)\) |
| C R1:paraboloid \( (y-270)^2=-500(z+18) \) | \( z=0.52963(z+143) \) | \((-156.9, 89.8)\) | \((-139.6, 98.9)\) |

Surface type of paraboloid in focusing mode A, cone in B and C are already afforded in ZEMAX corresponding to the type of Odd Sphere, Cone and Cylinder Pipe. For the other surface types, we need to create file of IGS in CAD then imported to ZEMAX for use. Shaded models of the three
focusing modes in ZEMAX are shown in figure 2 in which rays displayed are at random.

![Focusing modes in ZEMAX](image)

**Figure 2.** Shaded model of the three groups of reflecting surfaces in ZEMAX.

The two angular aberrations are: a) $\Delta \theta_L$, beam out-coming aberration (inclination of beam relative to the axis Z at the spot of laser source); b) $\Delta \theta_T$, flying aberration of thruster (inclination of focusing system relative to axis Z at the head of the focusing system). $d_L$ is the distance between laser source and the focusing system in figure 3(a).

![Angular aberrations](image)

**Figure 3.** Schematic diagram of the two angular aberrations: beam out-coming aberration (a) and flying aberration of thruster (b).

### 2.2 Laser Source Model and Monte Carlo Ray Tracing

Intensity distribution of laser beam is complex in practice, herein we use model of Gaussian beam of basic mode in which the distribution is axis-symmetric. In the polar coordinate, intensity distribution of laser beam on the plane vertical to axis Z is specified by

$$I(r) = I_0 \exp \left( -\frac{2r^2}{\omega_0^2} \right)$$  \hspace{1cm} (1)

Where $r$ is the distance from center of the beam, $I_0$ is the maximum intensity on the cross-section of the beam, $\omega_0$ is radius of laser beam which represents the $r$ where the intensity is $1/e^2$ of $I_0$, as shown in figure 3. In the near field, $\omega_0$ can be assumed to be constant. If the power of the laser source is $P$, $I_0=2P/(\pi \omega_0^2)$.
Figure 4. intensity distribution of laser radiation on cross-section

The ray tracing in ZEMAX adopts Monte Carlo (MC) approach, which is a kind of stochastic simulation method. Fundamental thought of MC approach is assuming the laser source as consisted of large quantity of mutually independent rays, while the emitting position or direction of rays, whether the ray is absorbed on the reflecting surface and the propagation process such as diffraction are all determined by corresponding probability model. If the amount of rays is \( N \), the average power of each ray is \( P/N \). Through tracing a ray till it is absorbed or escapes from the system then another ray launched, and with a large amount of rays repeating this process, stable statistic results would be gained. Herein, total reflection will occur when the traced ray reaches reflecting surface.

According to the axis-symmetry of intensity distribution of Gaussian beam, the probability model of ray emitting at the polar angle \( \theta \) is

\[
\theta \sim \frac{1}{2\pi}
\]

At \( r \), the probability model is obtained through normalizing equation (1), then is

\[
r \sim \frac{2}{\pi \omega_0^2} \exp \left( -\frac{2r^2}{\omega_0^2} \right)
\]

\( \theta \) and \( r \) are mutually independent random variables, so the ray emitting probability \( p(r_i, \theta_i) \) at \( r=r_i \), \( \theta=\theta_i \) is

\[
p(r_i, \theta_i) = \frac{1}{\pi \omega_0^2} \exp \left( -\frac{2r_i^2}{\omega_0^2} \right)
\]

For the computation of intensity distribution on the focusing plane, the plane is partitioned to a number of square grids, and then the sum of ray power absorbed in a grid divided by the grid area yields the result to the corresponding grid.

2.3 Focusing Performance Parameters

\( I_{\text{max}} \) and \( R_{\text{RMS}} \) are defined to assess the focusing performance of focusing system, where \( I_{\text{max}} \) is the peak intensity on the focusing plane representing whether the radiation intensity reaches breakdown threshold of the air (1\( \times10^7 \)W/cm²); \( R_{\text{RMS}} \) is

\[
R_{\text{RMS}} = \sqrt{\frac{\sum_{i=1}^{j} R_i^2}{j}}
\]

Where, \( j \) is the total number of rays absorbed by focusing plane through twice reflecting, and \( R_i \) is the distance between the ray of No.\( i \) and the ideal focus (\( x=y=0 \)) on the plane. \( R_{\text{RMS}} \) roughly represents deviation degree of laser spot from the ideal focus.

3. Simulation results and analyses
\( \alpha_v = 25 \text{mm} \), number of random rays \( N = 10^5 \) which can yield little fluctuating results, and the power of pulsed laser 3MW were set in ZEMAX. The focusing plane is set in absorption mode and its size is changing with the laser spot area while \( 25 \times 25 \) grids was guaranteed in every square millimeter. Intensity distribution on the focusing plane is continuous in reality, but what the MC tracing obtained is discrete and inconvenient for observation and analysis. So the results of computing were smoothened by 5 times.

3.1 Influence of flying aberration of thruster on focusing performance

When \( \Delta \theta_T \) increases, variation of \( I_{\text{max}} \) and \( R_{\text{RMS}} \) are shown in figure 5 and figure 6. \( I_{\text{max}} \) in the three focusing modes all decrease rapidly, but the tendencies of decreasing are apparently different. In focusing mode A, \( I_{\text{max}} \) drops monotonically with \( \Delta \theta_T \): \( \Delta \theta_T = 1^\circ \), \( I_{\text{max}} \) falls to \( 2.94 \times 10^8 \text{W/cm}^2 \) that is 4 times less than \( \Delta \theta_T = 0^\circ \); \( I_{\text{max}} \) falls to \( 7.9 \times 10^6 \text{W/cm}^2 \) that is below the breakdown threshold of the air at \( \Delta \theta_T = 5^\circ \). As for B, the decreasing tendency is less steep than A: \( \Delta \theta_T = 1^\circ \), \( I_{\text{max}} \) falls almost 10 times less than \( \Delta \theta_T = 0^\circ \) drastically; but between \( \Delta \theta_T = 1^\circ \) ~ \( 9^\circ \), the curve goes through a slow decreasing process, and falls below \( 1 \times 10^7 \text{W/cm}^2 \) at \( \Delta \theta_T = 10^\circ \). In C, the decreasing amplitude of \( I_{\text{max}} \) is steeper than the other two modes: \( I_{\text{max}} \) is less than \( 1 \times 10^7 \text{W/cm}^2 \) at just \( \Delta \theta_T = 3^\circ \) with \( 9.7 \times 10^6 \text{W/cm}^2 \), then the decreasing tendency is slowed down gradually. Inversely, for the three modes, \( R_{\text{RMS}} \) all increase linearly along with \( \Delta \theta_T \) and the increasing slopes from more to less are A, B, C orderly. At \( \Delta \theta_T = 0^\circ \), \( R_{\text{RMS}} \) are all around zero point reasonably; \( \Delta \theta_T = 10^\circ \), 83mm, 52mm and 24mm for focusing mode A, B and C.

![Figure 5. \( I_{\text{max}} \) changing with \( \Delta \theta_T \)](image)

On the focusing plane, focusing spot is defined as the area where the intensity is larger than 0 and the ignition region is the area of larger than \( 1 \times 10^7 \text{W/cm}^2 \). Relative intensity is the value of practical intensity divided by \( 1 \times 10^7 \text{W/cm}^2 \). For the research of flight route of the thruster, the position and shape of ignition region are very meaningful.

Relative intensity distributions on focusing plane with \( \Delta \theta_T \) are shown in figure 7. We can see distinctly dissimilar evolution of focusing spot and ignition region under different \( \Delta \theta_T \) for different focusing mode. Generally, a tendency of division of ignition region is shown in both focusing mode A and B, while in C exhibits a region of steadily expanding round. When \( \Delta \theta_T = 0^\circ \), there is no aberration and a round ignition region with center at the focus and radius of nearly 0.4mm is displayed in the three modes uniformly. At \( \Delta \theta_T = 1^\circ \), an ignition region shaped with two joined annuluses and a round of high intensity in the center has a deviation of almost 6mm from the focus in focusing mode A; in B, an upside-wide annulus ignition region with radius about 1.1mm has a deviation of nearly 5mm; in C, the ignition region is also an annulus with radius about 2mm, but its center is at the focus. At \( \Delta \theta_T = 3^\circ \), the two joined annuluses are stretched to two separated tilting elliptical loops at the bottom of which the
intensity is much higher while lower at the outsides and the deviation is almost 16mm in mode A; in B, deviation of nearly 11mm, two inter-tilting annuluses are also shown and the intensity at their overlapped bottom is relative high; in C, the ignition region can not be formed and the focusing spot is still a center-in-focus annulus but the area is broader with radius of nearly 7mm.

| Δθ_L/° | Scale      |
|------|-----------|
| 0    | 0         |
| 1    | 10        |
| 3    | 20        |

**Figure 7.** distribution of relative intensity on the focusing plane at certain Δθ_L

From the results above, we can conclude that distinctive falling tendencies of the focusing performance parameters and evolutions of the ignition region mark different focusing modes when Δθ_L exits. In focusing mode C, the RMS is the least and the shape of ignition region is focus-symmetric all along with Δθ_L, which could be beneficial for the stabilization of thruster.

### 3.2 Influence of beam out-coming aberration on focusing performance

The variations of I_max and R_RMS along with the Δθ_L are shown in figure 8 and figure 9 under \(d_L = 1000\)mm. On the whole, the falling tendencies in the three modes are nearly coincident, and so are their focusing performances. I_max all decrease steeply by an order-of-magnitude or more and the decreasing slopes from more to less are C, A, B with relatively slight contrast. At \(\theta_L = 0.5^\circ\), I_max falls almost ten times than there is no aberration in the three modes and I_max in B is a little bigger; \(\theta_L = 2^\circ\), the I_max in A and C are \(8.9 \times 10^6\)W/cm² and \(9.3 \times 10^6\)W/cm² all below the breakdown threshold of the air, while in B it is \(1.57 \times 10^7\)W/cm²; \(\theta_L = 2.5^°\), I_max are all below \(1 \times 10^7\)W/cm². The ascending slopes of R_RMS from more to less are C, A, B and all rise from zero. At \(\theta_L = 2.5^\circ\), R_RMS are 9.2mm, 10mm, and 12mm for focusing mode B, A and C.
Figure 8. $d_l=1\text{m}$, $I_{\text{max}}$ changing with $\Delta \theta_l$. Intensity distribution on the focusing plane when $\Delta \theta_l$ exits and $d_l=1\text{m}$ is shown in figure 10. We can see that the focusing spots are all shaped of annulus in the three focusing modes and the intensity in upper part which is along the direction of aberration is stronger than the bottom, while the area of focusing spot in focusing mode B is the least corresponding to $R_{\text{RMS}}$ of C in figure 9. At $\Delta \theta_l=0.5^\circ$, the ignition regions are all annulus and intensity distributions are symmetric along axis Y; the radii of the annulus regions from bigger to smaller is C, A, B orderly; the intensity in B is apparently stronger than the other two. At $\Delta \theta_l=1^\circ$ and $\Delta \theta_l=2^\circ$, the characteristic of intensity distributions is like the $\Delta \theta_l=0.5^\circ$, but the ignition regions have degraded to shape of circular arc and the focusing spots expand to broader annuluses.

Figure 9. $d_l=1\text{m}$, $R_{\text{RMS}}$ changing with $\Delta \theta_l$. 

| $\Delta \theta_l/^\circ$ | Scale |
|-------------------------|-------|
| 0.5                     | 0.95  |
| 1                       | 6.66  |

| Focusing mode A | Focusing mode B | Focusing mode C |
|-----------------|-----------------|-----------------|
| ![Image](image1.png) | ![Image](image2.png) | ![Image](image3.png) |
Figure 10. distribution of relative intensity on the focusing plane at certain $\Delta \theta_L$ ($d_L=1\text{m}$)

When $\Delta \theta_L$ exists, the intensity distributions in the three focusing modes are quite similar: the focusing spots all expands roundly and intensities decrease; the ignition regions evolve from the shape of annulus to arc with the area reduced. Coupled with the results of figure 8 and figure 9 that in focusing mode B the ignition region will disappear in the last and the spot deviation is the least, focusing performance of B is a little better. It should be noted that the existence of $\Delta \theta_L$ will bring in $\Delta \theta_T$, because the straying ignition area result in unbalanced force on the nozzle that will incline the thruster.

3.3 Influence of the distance of laser source on focusing performance

Figure 11 and figure 12 are the dependences of $I_{\text{max}}$ and $R_{\text{RMS}}$ on the $d_L$, when $\Delta \theta_L=1^\circ$. Mainly, as the $d_L$ increases, $I_{\text{max}}$ in the three focusing modes all ascend within a narrow range at first, and then decrease rapidly. When $d_L$ increases from 0 to 0.5m, the $I_{\text{max}}$ in focusing mode B rises from $6.1\times10^7\text{W/cm}^2$ to $7.04\times10^7\text{W/cm}^2$; while $I_{\text{max}}$ in A and C rise from $3.96\times10^7\text{W/cm}^2$ and $3.82\times10^7\text{W/cm}^2$ to $5.04\times10^7\text{W/cm}^2$ and $4.78\times10^7\text{W/cm}^2$ respectively at $d_L=0~1\text{m}$. At the descending phase when $d_L=1.5\text{m}~2.5\text{m}$, $I_{\text{max}}$ in the three modes are close and fall below the breakdown threshold of the air at $d_L=2.5\text{m}$. As for $R_{\text{RMS}}$, the figure shows a stationary process at $d_L=0~1\text{m}$ with the value around 3.1mm, 2.7mm and 3.6mm for focusing mode A, B and C, after $d_L=1\text{m}$ the $R_{\text{RMS}}$ all rise uniformly with the rising slope decreasing gradually. At $d_L=2.5\text{m}$, $R_{\text{RMS}}$ in focusing mode A, B, and C are 4.21mm, 3.71mm and 5.04mm respectively.

Figure 11. $\Delta \theta_L=1^\circ$, $I_{\text{max}}$ changing with $d_L$

We can see that the distance of laser source in a definitive range won’t influence the focusing performance when the beam out-coming aberration exists, but escaping the very range will result in remarkable falling focusing performance.

Figure 12. $\Delta \theta_L=1^\circ$, $R_{\text{RMS}}$ changing with $d_L$
4. Conclusions
Simulating the laser focusing systems by available software is a convenient and effective way. Modeling of focusing systems is a significant diagnostic and design development manner. Though optical design software is capable of simulating these systems, model construction is not trivial. Simulation accuracy counts on several factors: 1) understanding of the optical problem, 2) accurate computation of the physical model of the reflecting surfaces, 3) the amount of random tested rays, which means more rays tested helps more accurate results, but huge amount of rays being tested will consume computer resource highly and cost a very long time.

Studies show even insignificant aberrations will result in steep falling performance for any focusing mode and strong deviation of beam that directly result in asymmetry ignition area and unbalanced thruster simultaneously. So it strongly demands the directional precision of laser beam, and the attitude control system is indispensable for laser thrusters. While for the three modes, different aberrations cause distinctive falling tendencies of focusing performance: flying aberration of thruster shows absolutely different falling tendencies of focusing performance parameters and evolutions of ignition region; while out-coming aberration of laser beam brings similar falling tendencies and the ignition region; the distance of laser source bounded in certain range won’t influence the focusing performance when the previous aberration exists.

With only two angular aberrations investigated, it is not safe to recommend one focusing mode superior to another. Other aberrations such as manufacture errors, thermal deformations and wavefront aberrations of the beam are not considered. These aberrations could couple and will arouse greater falling focusing performance. The eventual conclusion is each focusing mode has its points, and in practice the choice of focusing mode should take into account which aberration is prominent.

References
[1] Ageichik A A , Egorov M S, Rezunkov Y A, Safronov A L and Stepanov V V 2004 Experimental study on thrust characteristics of airspace laser propulsion engine Sec. Int. Symp. on Beamed Energy Propulsion(Sendai, Japan, 20-23 Oct. 2003) (AIP Conf. Proc. vol 702) ed Kimiya Komurasaki (New York: Proc. AIP) pp 49-60
[2] Sasoh A, Yu X, Ohtani T, Kim S and Jeung I S 2004 In-Tube Laser propulsion: performance and application prospects Sec. Int. Symp. on Beamed Energy Propulsion(Sendai, Japan, 20-23 Oct. 2003) (AIP Conf. Proc. vol 702) ed Kimiya Komurasaki (New York: Proc. AIP) pp 61-67
[3] Shi H B, Cheng Z G, Jiang J Li X Q, Xu G L and Xia J A 2000 Study on misalignment of parabolic mirror in lightcraft vehicle High-Power Laser Ablation III (Proc. SPIE vol 4065) ed Phipps C R pp 371-378
[4] Feikema D 2000 Analysis of the laser propelled lightcraft vehicle 31st AIAA Plasma dynamics and Lasers Conf. (Denver CO, US, 19-22 June, 2000) AIAA-2000-2348 pp 1-14
[5] Wen M, Hong Y J and Li Q 2003 Study of the focus characteristics of the laser lightcraft J. Equipment Command & Technol. 14(4) 93-7