Optics Communications 368 (2016) 123–128

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

A coordinate transformation method for calculating the 3D light intensity distribution in ICF hohlraum

Zhili Lin [a,*], Xiaoyan Li [a], Kuixia Zhao [b], Xudong Chen [a], Mingyu Chen [a], Jixiong Pu [a]

[a] Fujian Provincial Key Laboratory of Light Propagation and Transformation, College of Information Science and Engineering, Huaqiao University, Xiamen 361021, China

[b] Department of Municipal Engineering, Guangdong Technical College of Water Resources and Electric Engineering, Guangzhou 510635, China

ARTICLE INFO

Article history:
Received 8 December 2015
Received in revised form
4 February 2016
Accepted 5 February 2016
Available online 11 February 2016

Keywords:
Inertial confinement fusion
Hohlraum
Light intensity distribution
Coordinate transformation

ABSTRACT

For an inertial confinement fusion (ICF) system, the light intensity distribution in the hohlraum is key to the initial plasma excitation and later laser-plasma interaction process. Based on the concept of coordinate transformation of spatial points and vector, we present a robust method with a detailed procedure that makes the calculation of the three dimensional (3D) light intensity distribution in hohlraum easily. The method is intuitive but powerful enough to solve the complex cases of random number of laser beams with arbitrary polarization states and incidence angles. Its application is exemplified in the Shenguang III Facility (SG-III) that verifies its effectiveness and it is useful for guiding the design of hohlraum structure parameter.

1. Introduction

Inertial confinement fusion (ICF) is an intriguing type of fusion energy research that attempts to initiate nuclear fusion reactions by heating and compressing a nuclear fuel target [1]. In an indirect-drive laser ICF system, a gold cylindrical hohlraum is often used, which is irradiated with laser beam cones from either side on its inner wall surface where the laser light energy is converted into X-ray radiation that drives the even ablation and compression of the capsule [2,3]. Obtaining high uniformity of the initial laser irradiation is the key to achieving a successful implosion and suppressing the harmful laser-plasma interaction processes such as the self-focusing filamentation [4]. Therefore, it is necessary and meaningful to study the optical intensity distribution both on the hohlraum wall and in the inner space of hohlraum.

For this purpose, Huang et al. have proposed a method based on the idea of layering calculation, combining the algorithm of fast Fourier transform with the technology of numerical fitting, to calculate the light intensity distribution on the curved observation surface [5]. Following the methodology, the spatio-temporal evolution of the optical field on a hohlraum wall at the rising edge of a flat-topped pulse was studied by Jiao et al. in Ref. [6]. However, the method was obscure and complex to program even for the case of only single-beam incidence on the inner curved wall of hohlraum. Zhang et al. have numerically analyzed the beam uniformity methods by using the random phase plate and given the light intensity distribution at the entrance orifices or on the hohlraum wall [7]. The method discussed therein was only suitable for configuration with single laser beam entrance for each side of hohlraum. For a practical ICF system, the number of laser beam can be up to more than one hundred such as in the National Ignition Facility (NIF), 192 laser beams deliver up to 1.8 MJ of light into the hohlraum [8], that would greatly increase the difficulty and computing burden by using the previous methods.

In this work, we propose a simple, intuitive and robust method for calculating the three-dimensional (3D) light intensity distribution in the hohlraum, including the inner wall surface. The reason for this simplicity goes for the fact that instead of the rotation and translation of each light beam itself, the position coordinate of any point of interest for light intensity calculation in the hohlraum is transformed to the transformed coordinates relative to the original single beam, which is firstly assumed to propagate along and symmetrical to the z axis by using the coordinate transformation matrices that represent coordinate rotations and translation. Meanwhile, the polarization of electric field of each beam change accordingly to such coordinate transformation. With these considerations, one can calculate the light intensity distribution in the hohlraum for any case with the entrance of random number of laser beams with arbitrary polarization states and incidence angles.

* Corresponding author.
E-mail address: zllin2008@gmail.com (Z. Lin).

http://dx.doi.org/10.1016/j.optcom.2016.02.008

2. Methodology

As depicted in Fig. 1, the symmetric axis of hohlraum is set as the z axis and its left disk end as the xOy plane to establish the Cartesian coordinate system. The inner space of hohlraum is L in length and $2R$ in diameter. Without loss of generality, we only illustrate the incidence of the ith beam of the total N beams for the sake of clarity in Fig.1. The ith beam has a polar angle θ_i and an azimuthal angle ϕ_i and its defocus amount after propagating from the lens is $(\Delta x_i, \Delta y_i, \Delta z_i)$. In general, to achieve the final position and posture of the ith beam relative to the hohlraum from its initial state along the horizontal z axis as we proposed, a five-step procedure should be followed:

(1) Consider the initial arrangement of the ith laser beam propagating horizontally with its symmetrical axis overlapped with the z axis and with its waist center coincided with the original point O. Assume that the ith beam outgoing from the lens has a 3D electric field given by

$$\boldsymbol{E}_{0i}(x, y, z) = \{E_{0xi}(x, y, z), E_{0yi}(x, y, z), E_{0zi}(x, y, z)\}, \tag{1}$$

where E_{0xi}, E_{0yi} and E_{0zi} are the three components of $\boldsymbol{E}_{0i}$ shown as a three-component list to represent the electric field vector. It is usually known at first or can be conveniently calculated from a specific type of light beams that propagate through the vertically placed lens systems according to the scalar diffraction theory [9].

(2) In the xOz plane, rotate the ith light beam around the y axis with its polar angle θ_i (positive in the counter-clockwise direction from the inverse perspective of y axis) to set the beam inclination angle. Then the expression for electric field becomes

$$\boldsymbol{E}'_i(x, y, z) = \boldsymbol{E}_{0i}(x', y', z')R_{yi}^{-1}, \tag{2}$$

where

$$(x'y'z') \Leftrightarrow (xyz)R_{yi} \tag{3}$$

and

$$R_{yi} = \begin{bmatrix} \cos\theta_i & 0 & \sin\theta_i \\ 0 & 1 & 0 \\ -\sin\theta_i & 0 & \cos\theta_i \end{bmatrix}. \tag{4}$$

(3) Secondly, rotate the light beam $\boldsymbol{E}'_i$ around the z axis with the specified azimuthal angle ϕ_i (positive in the counter-clockwise direction from the inverse perspective of z axis) in order to realize the setting of evenly arranged beams on the same incidence ring. The electric field changes to

$$\boldsymbol{E}''_i(x, y, z) = \boldsymbol{E}_{0i}(x'', y'', z'')R_{yi}^{-1}R_{zi}^{-1}, \tag{5}$$

where

$$(x''y''z'') \Leftrightarrow (x'y'z')R_{zi} \tag{6}$$

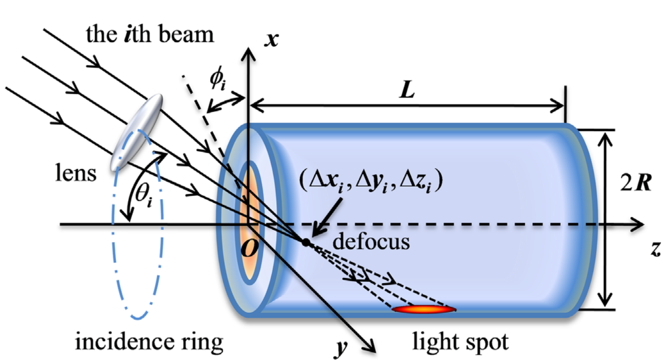

Fig. 1. Schematic diagram for the injection of the ith laser beam, for example, into the hohlraum with detailed notation for some key structural parameters.

and

$$R_{zi} = \begin{bmatrix} \cos\phi_i & -\sin\phi_i & 0 \\ \sin\phi_i & \cos\phi_i & 0 \\ 0 & 0 & 1 \end{bmatrix}. \tag{7}$$

(4) Further translate the light beam with its waist center shifting from the original point O to the specified point $(\Delta x_i, \Delta y_i, \Delta z_i)$ to set the defocusing amount. For the spatial translation of coordinate system affect the coordinates of the position rather than the direction of electric field vector, the expression for the updated electric field becomes

$$\boldsymbol{E}'''_i(x, y, z) = \boldsymbol{E}_{0i}(x''', y''', z''')R_{yi}^{-1}R_{zi}^{-1}, \tag{8}$$

where

$$(x''' \ y''' \ z''') \Leftrightarrow (x'' - \Delta x_i \ \ y'' - \Delta y_i \ \ z'' - \Delta z_i). \tag{9}$$

Following the previous steps, the mission of setting of the waist center position, inclination angle and azimuth angle of the ith laser beam is accomplished.

(5) Finally, in order to calculate the light intensity after the previous transformations at the point position (x''', y''', z''') in the hohlraum, it should be transformed to its corresponding position (x, y, z) in the initial laser beam coordinates. The inverse transform $(x''', y''', z''') \Rightarrow (x, y, z)$ is needed and it can be easily realized by applying Eqs. (9), (6) and (3) in sequence. Thus based on the principle of superposition of light waves, the general expression for the light intensity distribution in the hohlraum in the case of total N beam entrance is obtained:

$$I(x''', y''', z''') = \frac{n}{2\mu c}\left|\sum_{i=1}^{N}\boldsymbol{E}'''_i(x'', y'', z''')\right|^2 = \frac{n}{2\mu c}\left|\sum_{i=1}^{N}\boldsymbol{E}_{0i}(x, y, z)R_{yi}^{-1}R_{zi}^{-1}\right|^2, \tag{10}$$

where c is the speed of light in vacuum, while n and μ are the refractive index and permeability of media in which the N beams propagate, respectively. If the beams are incoherent to each other, the expression is simplified to

$$I(x''', y''', z''') = \frac{n}{2\mu c}\sum_{i=1}^{N}\left|\boldsymbol{E}'''_i(x''', y''', z''')\right|^2 = \frac{n}{2\mu c}\sum_{i=1}^{N}\left|\boldsymbol{E}_{0i}(x, y, z)\right|^2, \tag{11}$$

where the light intensities for the N laser beams can be summed arithmetically and note that $\left|R_{yi}^{-1}R_{zi}^{-1}\right| = 1$.

3. Examples and results

As an example for the proposed method, consider the scheme of Shenguang III Facility (SG-III) for calculating the light intensity distribution [10,11]. The modeled golden hohlraum is assumed with the optimized size [12], that is, 1mmin diameter and 1.7mmin length. A total of 48 beams of 10-order super-Gaussian lasers with wavelength 351 nm enter the hohlraum through the two entrance orifices on the left and right ends. For each end, 24 beams are divided into four groups with different inclination angles. The first two groups with polar angles $\theta_1 = 28.5^\circ$(4 beams) and $\theta_2 = 35^\circ$(4 beams) forms the inner-cone rings with equal interval of azimuthal angle $\Delta\varphi = 90^o$. The other two groups with inclination angles $\theta_3 = 49.5^\circ$(8 beams) and $\theta_4 = 55^\circ$(8 beams) forms the outer-cone rings with equal interval of azimuthal angle $\Delta\phi = 45^o$. In the