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Optical field distribution on a hohlraum wall during indirect laser-driven inertial confinement fusion

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ABSTRACT

A model to calculate the optical field distribution of quadruplet beams on a hohlraum target wall is presented. This model combines geometrical ray tracing, coordinate transformation, and Fresnel diffraction integral to capture the quadruplet beams propagating in four different directions and the typically non-planar geometry of the hohlraum wall. The results demonstrate that the optical field distribution arises mainly from individual beam diffraction, and the interference with other beams in the quadruplet hardly devotes to the distribution. A movie is also produced to interpret the spatio and temporal evolution of the optical field on a cylindrical hohlraum wall.

1. Introduction

In indirect laser-driven inertial confinement fusion (ICF) [1,2], lasers are focused on the inner wall of a hohlraum target to generate X-rays, which more uniformly irradiate a target pellet. Laser beams in typical giant high-power laser drivers, such as those at the National Ignition Facility (NIF) [3] and the Laser Mégajoule (LMJ) Project [4], propagate grouped together, usually in a 2×2 quadruplet, or quad. Different quads are focused into the target hohlraum through different final optics assemblies (FOAs) [5], which are distributed on the target chamber at different polar and azimuthal angles. In this manner, the target hohlraum is more completely and uniformly irradiated. As shown in Fig. 1, one quad is focused at the center of the laser entrance hole (LEH) to irradiate the hohlraum wall; the beam spot on the wall appears as four separated spots instead of the desired single whole beam spot. To develop the best optical design of the target area, and the hohlraum target design, itself, requires analysis of the size, profile, and spacing between the individual spots and the optical field distribution within the beam spots. Such analysis will allow researchers to better understand the beam spots in the hohlraum wall, leading to improved laser driver design and X-ray generation processes.

Two issues make analytically calculating the beam spots difficult. First, the hohlraum target used in indirect driven ICF is typically a cylindrical hohlraum [6], a rugby hohlraum [7], or a spherical hohlraum [8,9]. As shown in Fig. 1, the cross-section of the beam quad and the cylindrical hohlraum is not a plane. Second, a wedged focus lens (WFL) is introduced in the FOA to focus and chromatically separate the beams [5]. The WFL directs the quad beams in separate directions from each other. Further, the four entrance planes of the WFL are not in the same plane. These issues make it difficult to calculate the optical field distribution on the inner wall of the hohlraum using existing beam propagating algorithms.

Jiao [10] reported a method combining a fast Fourier transform (FFT) with chromatography to calculate the spatio-temporal optical field distribution characteristics on a cylindrical hohlraum wall. However, their simulation modeled only one beam and chromatography principles do not suit the optical distribution generated by four beams propagating in four different directions. Studies on the beam conditions of the focus spots in both the NIF and LMJ [11,12] have been published. The plane used to detect the focus spot were all in planes perpendicular to the quad, and not a realistic hohlraum target wall surface, which is usually non-planar and has a certain angle with the quad. In this article, a model combining optical ray tracing and Fresnel diffraction integrals is proposed to calculate the beam spot generated by quad beams on the hohlraum wall. This model is not limited to the cylindrical hohlraum, but can calculate the optical distribution on spherical and other geometrically shaped targets.

2. Model and calculations

In calculating the conventional diffraction pattern of an optical field distribution on a plane [13], the calculating plane and the

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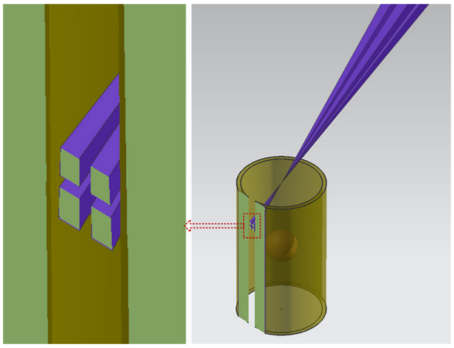

Fig. 1. Schematic of laser quad entrance into the hohlraum target. The beam spots appear as four distinct spots.

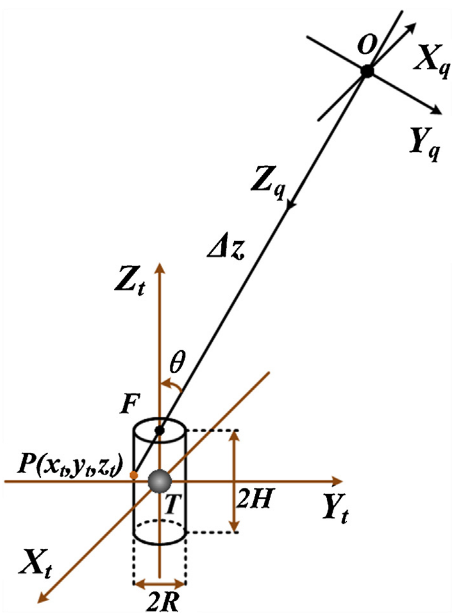

Fig. 2. Transformation relationships between TCCS($T-X_tY_tZ_t$) and QCS($O-X_qY_qZ_q$). Hohlraum diameter 2R and total length 2H. Polar angle θ.

laser emission plane must be parallel to each other. While in a quad, the emergence planes of the four laser beams are not coplanar with each other, or with the calculating plane on the hohlraum wall. Therefore, some modifications to the conventional calculations were required to calculate the optical field distribution with FFT [14]. First, the profile and shape of the beam spots on the hohlraum wall are obtained by a geometrical ray tracing method. The points in the area defined by the beam spots are then transformed into the four laser beam coordinate systems in two-step coordinate transformations. In each individual beam coordinate system, the optical field value of each transformed point is calculated by FFT. Finally, the actual optical field of the original point on the hohlraum wall is calculated as the interference of the four field values. This procedure is applied to each point in the originally defined area to acquire the whole beam spot optical field distribution.

The detailed calculation proceeds as follows: The target chamber coordinate system (TCCS), $T-X_tY_tZ_t$ is taken as the reference coordinate system. The hohlraum is a cylinder with the diameter *2R* and total length *2H*. Each quad has its own quad coordinate system (QCS), $O-X_qY_qZ_q$. Fig. 2 shows the position and rotating relationship between TCCS and QCS of the quad with the polar angle θ

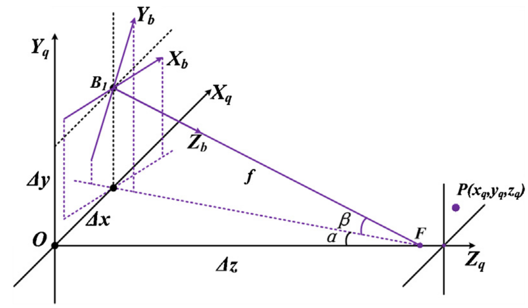

Fig. 3. Transformation relationships between QCS($O-X_qY_qZ_q$) and BCS($B_1-X_bY_bZ_b$). Distances between the quad center, beam center, and LEH center were Δx, Δy, and Δz. The lens rotated α and β degrees along Y_q and X_q axes, respectively. Focus length of the WFL *f*.

focused at LEH center F of the target hohlraum. Each quad has four different beam coordinate systems (BCSs); Fig. 3 illustrates the beam in the first quadrant, as an example. Its coordinate $B_1-X_bY_bZ_b$ can be transformed to QCS by translation and rotation. The transformation relationships between the three coordinate systems can be expressed as Eqs. (2-1) and (2-2), where Δx and Δy are the *x* and *y* translations, respectively, between the quad center and beam center, and Δz is the distance between the quad center and the LEH center. The focus length of the WFL *f* relates to these translation values as $f=\sqrt{(\Delta x)^2+(\Delta y)^2+(\Delta z)^2}$. A thin lens rotated α and β degrees along Y_q and X_q axes, respectively, simulates the simultaneous focusing and chromatic separation of the beams by the WFL, where $\tan\alpha=\Delta x/\Delta z$ and $\sin\beta=\Delta y/f$. The coordinates of a point in all three systems are (x_t, y_t, z_t), (x_q, y_q, z_q), and (x_b, y_b, z_b), respectively.

$$\begin{bmatrix} \cos\alpha & -\sin\alpha\sin\beta & -\sin\alpha\cos\beta \\ 0 & \cos\beta & -\sin\beta \\ \sin\alpha & \cos\alpha\sin\beta & \cos\alpha\cos\beta \end{bmatrix}\begin{bmatrix} x_b \\ y_b \\ z_b \end{bmatrix}=\begin{bmatrix} x_q-\Delta x \\ y_q-\Delta y \\ z_q \end{bmatrix} \quad (2\text{-}1)$$

$$\begin{bmatrix} -1 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta \\ 0 & -\sin\theta & -\cos\theta \end{bmatrix}\begin{bmatrix} x_t \\ y_t \\ z_t-H \end{bmatrix}=\begin{bmatrix} x_q \\ y_q \\ z_q-\Delta z \end{bmatrix} \quad (2\text{-}2)$$

We calculated the beam spot optical field distribution of the FOA [5] in the outer cone of the NIF target chamber as an example. The polar angle was $\theta=50°$; the distances between the quad center, beam center, and LEH center were $\Delta x=278.3$ mm, $\Delta y=316.25$ mm, and $\Delta z=7688.47$ mm; and focus length was $f=7700$ mm. The hohlraum target was cylindrical, with $R=2.5$ mm and $H=5$ mm. The laser had a wavelength $\lambda=351$ nm, beam size 400 mm × 400 mm, and a 10-order super Gaussian beam with waist radius $\omega=200$ mm.

All parameters were first transformed into TCCS, and underwent ray tracing. The resulting beam spot shape and profile are shown in Fig. 4. The calculating area was defined to cover the total beam spots area, indicated by the red dotted rectangle in Fig. 4. Each point in the calculating area was transformed from TCCS coordinates, to QCS, and then into all four BCS, $B_i-X_{bi}Y_{bi}Z_{bi}$, $i=1, 2, 3, 4$. For $P(X_{bi},Y_{bi},Z_{bi})$ in BCS, the optical field distribution in the plane $z=Z_{bi}$ can be easily calculated by FFT. However, the point (X_{bi},Y_{bi}) was not necessarily one of the sample dots in the plane $z=Z_{bi}$, so 2D interpolation was performed to acquire the precise optical field. The final optical intensity distribution on the hohlraum wall, shown in Fig. 5, was calculated by interfering the optical fields from the four BCSs.