Optik 125 (2014) 6123–6126

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Incoherent combination of fiber lasers using a collimating and focusing optical system in fiber-based laser fusion

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ARTICLE INFO

Article history:
Received 30 October 2013
Accepted 3 June 2014

Keywords:
Beam combination
Fibers
Laser fusion

ABSTRACT

The incoherent combination of fiber laser beams using a collimating and focusing optical system in fiber-based laser fusion is theoretically and numerically studied. The propagation of the fiber lasers passing through the optical system is analyzed by the ABCD law. The super-Gaussian fitting is performed to study the synthetic intensity profile near the focal spot quantitatively. The intensity profile of the combination beam is dependant on the defocusing distance, the number of the fibers, the separation of the fibers, and the beam expansion ratio of the collimating system.

1. Introduction

The driver efficiency is one of the key issues for the realization of inertial fusion energy (IFE) power plants based on the inertial confinement fusion (ICF). Benefiting from the fast development of fiber laser techniques [1], a new drive system scheme based on the diode-pumped fiber amplification network (FAN) has been proposed [2]. Compared with the bulk laser driver, the fiber-based laser driver provides a higher wall-plug-to-laser efficiency. The conversion efficiency is in the order of 30–40% if the fiber laser system is operated in pulse mode [2,3]. Limited by the output capability of a single mode fiber amplifier, typically 10 mJ per pulse [4], the fiber-based laser driver calls for a huge number of fibers (in the order of 10^7) to ignate the fusion fuel. As a trade off, the fiber lasers can be arranged with more flexibility compared with the bulk laser. The fibers are supposed to irradiate the fusion target separately or they packed in bundles. In both arrangement schemes, the optical system should be well designed to couple the energy of the fiber lasers into the fusion target efficiently. In the first arrangement scheme, each fiber is directly coupled by a single lens into the fusion target [5]. In the second scheme, the fiber lasers (considered as off-axis beams) are supposed to pass though a compound lens system and overlap each other near the focal spot. The combination of the off-axis laser beams passing through a first-order optical ABCD system has been studied intensively [6–11]. In the case of fiber-based ICF research, the intensity profile of the combination beam should be studied in detail, as it plays an important role in smoothing the irradiation inhomogeneity. In direct drive ICF, the irradiation inhomogeneity is considered to be lower than 1% (RMS) to avoid the Rayleigh–Taylor instabilities [12]. In this paper, a collimating and focusing optical system has been designed to couple the energy of the fiber bundles into the fusion target based on the requirements of the laser fusion system. The propagation of the fiber lasers passing though the optical system is theoretically analyzed. The synthetic intensity profile determined by the overlap of the beam spots is studied by numerical simulations. Numerical surveys show that the synthetic intensity profile is dependant on the defocusing distance, the number of the fibers, the separation of the fibers, and the beam expansion ratio of the collimating system. Near the focal spot, the change of the intensity profile within the region of the target size can be neglected.

2. Theoretical analysis

In the fiber-based ICF scheme, the large mode area (LMA) fiber is employed for its high output capability [2]. It is supposed that the LMA fibers are operated at the fundamental mode which indicates that the output intensity profile can be estimated by the Gaussian profile. Compared with the bulk lasers, the fiber lasers can be arranged with more flexibility. Fig. 1 plots the diagrams of the two typical arrangement schemes. In this paper, we focus on the study of the laser beam propagation in the second arrangement scheme showed in Fig. 1(b). The details of first arrangement scheme can be found in [5].

In the second arrangement scheme, the fibers are packed in N bundles. Each of the fiber bundles corresponds to a single beamlet in the bulk laser based ICF system and contains about n_F/N fibers, where n_F are the total number of the fibers around the target cham-

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http://dx.doi.org/10.1016/j.ijleo.2014.06.106
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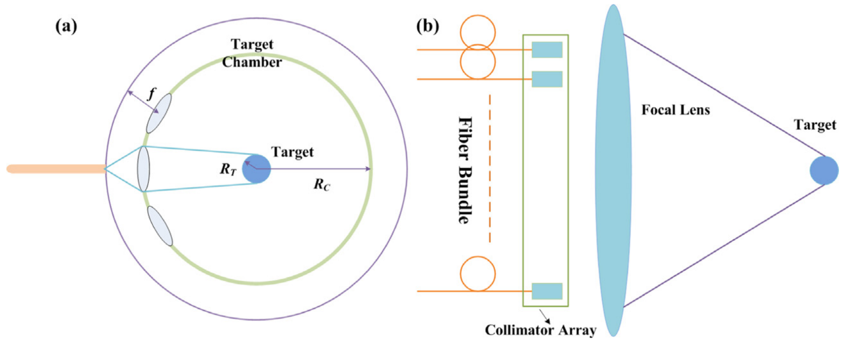

Fig. 1. Diagrams of (a) the arrangement of fiber lasers irradiating the fusion target separately and (b) the arrangement scheme that the fibers are packed in bundles.

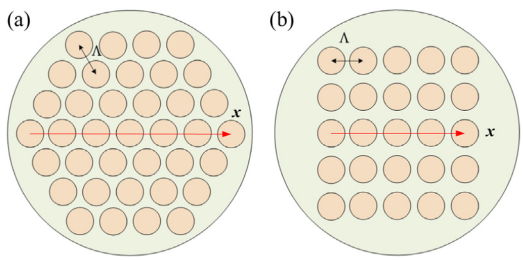

Fig. 2. Hexagon (a) and rectangular (b) distribution of the fibers within a fiber bundle. Λ is the separation distance of two neighboring fibers. The propagation of the laser beams is studied in the *x* direction.

ber. The collimators showed in Fig. 1(b) are designed based on defocusing telescopic system to expand the laser beams emitted from the fibers. Then these beams are coupled by a focal lens with a large *F* number to irradiate the fusion target placed at the center of the target chamber. According to the typical chamber and target designs, we set the chamber size $R_C = 5$ m, and the target size $R_T = 1$ mm. The fibers within a bundle can be arranged with hexagon or rectangular distribution as shown in Fig. 2. However, to simplify the theoretical analysis, we only discuss the propagation of the laser beams in one of its symmetrical axis for each distribution. The theoretical derivation can be easily generalized in two-dimensional coordinate system.

Fig. 3 shows the propagation of the fiber beams within a fiber bundle passing though the collimating and focusing optical system. Each fiber beam is considered as a Gaussian beam with a beam waist w_0. The end of the fibers is distributed at the plane $z = 0$. To simplify the derivation, the fibers lie on the *x*-axis are studied. The fibers are distributed in line with a center-to-center separation Λ for neighboring fibers. We start from the optical field at the end of a fiber. The field distribution for the *m*th fiber whose center locates at $x = \eta$ can be expressed as:

$$E_m(x_\eta, z_\eta = 0) = \exp\left(-\frac{i\pi {x_\eta}^2}{q_0}\right), \quad \eta = m \cdot \Lambda, \quad q_0 = \frac{\pi w_0}{\lambda} i, \tag{1}$$

where (x_η, z_η) denotes the local Cartesian coordinate system. The transformation relation between the local axis and the global Cartesian coordinate system is given by:

$$\begin{cases} x_\eta = x - \eta = x - m \cdot \Lambda \\ z_\eta = z \end{cases}. \tag{2}$$

The collimators are designed based on the defocusing telescope system. Parameters of the collimator are carefully chosen to make sure that waist of the Gaussian beam locates at the end of the collimator. The propagation of the Gaussian beam described by Eq. (1) passing through the collimator which is considered as a first order ABCD optical system obeys the following equation [13]:

$$E_m(x_\eta, z_\eta = L) = \frac{E_0}{A_1 + B_1/q_1} \exp\left[-\frac{i\pi {x_\eta}^2}{q_1}\right], \quad q_1 = \frac{A_1 q_0 + B_1}{C_1 q_0 + D_1}. \tag{3}$$

A_1, B_1, C_1, D_1 are the elements of the ABCD matrix for the collimator. In the global coordinate system, E_m the optical field is expressed as:

$$E_m(x, z = L) = \frac{E_0}{A_1 + B_1/q_1} \exp\left[-\frac{i\pi (x-\eta)^2}{q_1}\right], \quad q_1 = \frac{\pi w_1^2}{\lambda} \cdot i, \tag{4}$$

where w_1 is the beam waist width of the Gaussian beam emitting from the collimator. The beam expansion ratio of the collimator is defined as $M_C = w_1/w_0$. The laser beam is then coupled by the main focal lens into the fusion target. At the plane $z = z_T$ the field distribution of the *m*th laser beam is expressed as:

$$E_m(x, y, z = z_T) = \frac{E_1}{A_2 + B_2/q_2} \exp\left\{-\frac{ik[x - (x_d - x_\varepsilon i)]^2}{2q_2}\right\}, \quad q_2 = \frac{Aq_1 + B}{Cq_1 + D} = q_2^R + q_2^I \cdot i, \quad x_d = \frac{\eta D_2}{D_2^2 + C_2^2 Z_1^2}, \quad x_\varepsilon = \frac{\eta C_2 Z_1}{D_2^2 + C_2^2 Z_1^2}, \quad Z_1 = \frac{\pi w_1^2}{\lambda}. \tag{5}$$

A_2, B_2, C_2, D_2 are the elements of ABCD matrix of the focusing system. E_m is actually the decentered Gaussian beam described in

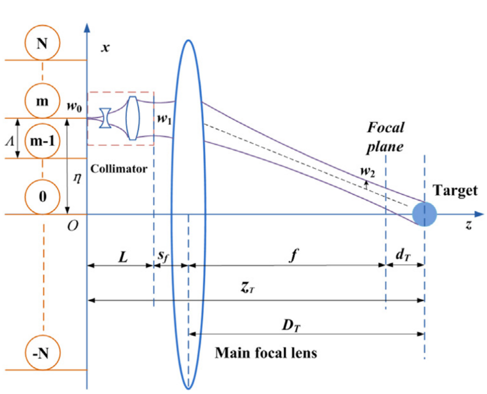

Fig. 3. The propagation of a fiber laser passing through the collimating and focusing optical system.