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Assembly modeling and error analysis of large laser optics

Hui Wang[a] Zhao Xiong[b,*] Chao Yao[a] Yiming Rong[a] Xiaodong Yuan[b]

[a] *Tsinghua University, Department of Mechanical Engineering, Beijing, China, 100084*
[b] *China Academy of Engineering Physics, Research Center of Laser Fusion, Mianyang, China, 621900*

* Corresponding author. Tel.: +86-15908219603; fax: +86-10-62773517. *E-mail address:* xiong_022111@163.com

Abstract

In the high power laser facility of China, 48 laser beams, passed and propagated by beampaths made up of thousands large optical units, should focus into the target centre better than 50 μm (RMS) within a few picoseconds, which poses technical challenges never seen before to technical institutions and industries. The assembly problem of large ICF optics, including to control and minimize the system's alignment error, is characterized by three crucial constraint factors, stringent positioning specifications, complex structure including thousands of components, and ambient input excitations, so, any feasible solution must be a result balancing those constraints. A significant priority in optical system assembly and mounting optimization is to develop the methodology integrated optical performance, structural response and assembly tolerances into a unified framework to find a balance among conflicting constraints. So the fundamental principles of the framework we have developed, based on a strategy of multi-loops assembly alignments and approximations to final stringent specifications, are discussed here. Error budget of large optics are allocated from the total positioning budget of beamline consisted of those large optics. And the large optics are pre-aligned and packaged very precisely into the modular opto-mechanical assemblies called line replaceable units (LRUs), with strict specifications. Once all LRUs are assembled on the support structure and formed an activated beamline, the beamline will meet its assembly performance, as the required 50 μm (RMS) positioning accuracy. The philosophy is demonstrated by an example of transport mirror LRU assembly design. A great advantage of proposed opto-mechanical modeling and analysis is to provide a promising choice for new assembly challenges in leading edge fields, some ultra-precise or fragile balance between the specifications and working conditions.

Key words: optical system precision assembly; opto-mechanical modeling; assembly error analysis

Keywords: assembly perforamcne analysis; optical precision assembly; opto-mechanical system;

1. Introduction

SG-III is an inertial confinement fusion (ICF) facility with 48 laser beams to create fusion conditions with controllable laboratory conditions, at China Academy of Engineering Physics [1]. In the high power solid-status laser system, there are thousands of large aperture optical components including laser glass, mirrors, lenses, and polarizers. Held in large opto-mechanical assemblies called line-replaceable units (LRUs) [2-3], these optics are designed as function-independent subsystems and must be manufactured and assembled with the most stringent requirements because that the position and direction of all beams must be sufficiently stable to allow their accurate alignment through the laser to the target and to maintain that alignment until the shot is complete. So the Optics Assembly Building (OAB), a Class-100 (ISO Class 5) cleanroom attached in SG-III facility, is built and all LRUs are assembled in the building with a condition of strict cleanliness and precise alignment. However, due to the fact that most technical requirements for large ICF optics are close to the limitations of state-of-the-art manufacturing, assembly and measurement technologies,

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there are huge challenges to assure the stringent specifications of large ICF optics mounting, installation and alignment [4].

2. Laser beam path and large optics error budget

SG-III laser system features 48 high-power laser beams that will produce 0.18 MJ energy of laser with about 0.35 micron wavelength. After fully operational, it will be the largest inertial confinement fusion research facility of China. As shown in the Figure 1 shows, each 3.75 kilojoules laser beamline consists of a multi-pass, regenerative amplifier followed by a power amplifier, a spatial filter to clean the beam, transport mirrors to convert laser path, and a final optics assembly before focusing on the micro-target. Since ICF experiments with SGIII will use a short pulse length of about one-to-twenty nanoseconds, the alignment-sensitive optical components in SGIII system must be aligned properly and remain stable with that alignment to position the beams on target as desired. The specific requirements for alignment include positioning the 48 beams within the clear apertures of the laser components, focusing them accurately through the far-field pinholes of the amplifier chain spatial filters, and delivering them to the precise locations specified on the target. For the alignment processes, the beam position on target is an error summation of all the contributors that displace the beams from their appropriate locations at the target. It requires that the RMS deviation in the position of the centroids of all beams from their specified aiming points shall not exceed 50 μm at the target. To develop stability requirements, the motion of optical components is related to beam position on target. While translations of lenses relate to translations of the beams on target, rotations of mirrors are multiplied by the focal length of the target result in translations of the beams on target. So the impact of optical component's errors to the beam position on target (denote as Δ_x) can be determined from the following equations [5-6]:

$$\Delta_{dueto\,Lens\,Motion} = n * \Delta_{Lens} * (f_{Target} / f_{Lens}) \quad (1)$$

$$\Delta_{dueto\,Mirror\,Motion} = n * (2 * \cos(\alpha) * \Delta\theta_{Mirror}) * f_{Target}) \quad (2)$$

Where, Δ_{Lens}, displacement of lens surface;

f_{Lens}, focal length of lens;

f_{Target}, focal length of target;

α, angle between incident beam and mirror normal;

θ_{Mirror}, displacement of lens surface;

n, since SGIII is a multi-pass laser system, number of times beam passes through or reflected by an optical element is considered.

Subsequently, with above discussions, each optical component belongs to the beamline can cause the laser to drift from its aligned position, the accumulative effect can be defined as follows:

$$T_{TAR} \approx f_{Target}[\sum_{i=1}^{N1} n(i)\Delta_{Lens} / f_{Lens(i)} + 2\sum_{j=1}^{N2} n(j)\Delta\theta_{M(j)}] \quad (3)$$

Considering the fact that there are more than 30 types of LRUs, when using above equations reversely, it provides a guideline for error budget allocation of beamline optics – a certain portion of the total error budget should be allocated to each optic in the beamline. This implies the fact that for a huge laser system with thousands of components, its error budgets are based on the philosophy of top-down design. What did in the design of NIF, another inertial confinement fusion facility, as some engineering data shown by Sommer and Bliss, also keep this rule. For instance, the total drift for 400×400 mm^2 sized large turning mirrors in the Target Area Building is only 0.68 microradians (μrad) for rotation and 6.8 microns (μm) for translation. This means the assembly structures and operational process shall be very precisely to meet the stringent requirements.

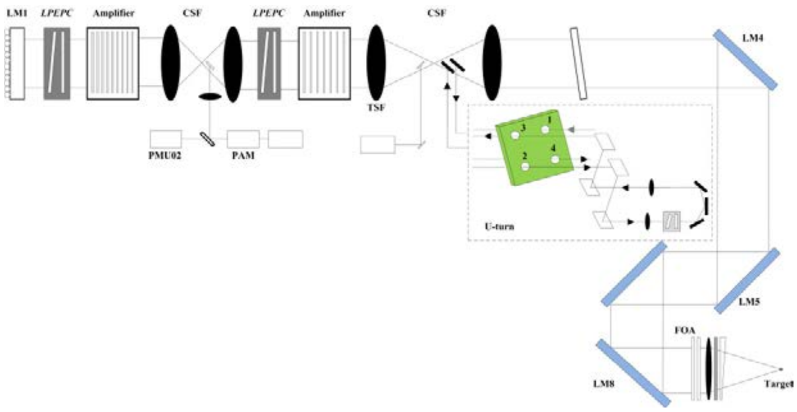

Fig.1 Laser path of SG-III

3. Large laser transport mirror and its alignment specifications

Before entering the target chamber, the laser beams travel through the switchyard, where they are redirected by