Micro-vibrating spatial filters-induced beam positioning stability in large laser system

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A dynamic beam propagation model of micro-vibrating spatial filters in inertial confinement fusion (ICF) facilities is built based on the additional beam in SG-II facility. The transfer matrix is then deduced, and the sensitivities of the beam positioning to the pellet in the target area to the vibrations of every spatial filter are analyzed, which indicates that the vibrations of spatial filters in the pre-amplify zone has less effects on beam positioning stability at the target. In addition, the vibrations of spatial filters in the main amplify zone dominates the beam positioning stability of the target, especially the vibration of the spatial filter SF_7.

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High-power laser apparatus for experiments on inertial confinement fusion (ICF) is a very precise large optical system. In such apparatus, many high-power laser beams target a pellet under the tolerance of below a few dozens of micrometers after long-distance propagation[1,2]. Therefore, any disturbances on the optics-such as those caused by ambient vibrations, acoustic vibrations, or thermal gradients-could reduce the targeting precision and lower the targeting success rate[3]. To enhance the stability of ICF apparatuses, researchers have done a lot of work. In Ref. [3], the structure vibration of the national ignition facility (NIF) was analyzed with the finite element model. The stability of mirror support systems in the NIF was discussed in Ref. [4]. In Ref. [5], the beam positioning stability passing through one vibrating spatial filter was analyzed. The beam positioning is more sensitive to vibrations of spatial filters near the target area, but no theoretical analysis has been found yet. This letter built the whole beam propagating model of ICF apparatuses and analyzed the whole beam propagation in the spatial filters to illustrate the influence of every spatial filter in a large laser system. For better understanding, the additional beam in SG-II facility was particularly analyzed, and the most sensitive spatial filter was found to be SF_7.

ICF apparatuses mainly consist of mirrors and spatial filters in optical systems, where every spatial filter had two confocal convex lenses. Leaving out the mirrors, the schematic of one laser beam in an ICF optical system is illustrated in Fig. 1. Spatial filters are numbered as SF_i ($i = 0, \cdots, n$) and the two confocal convex lenses are named as $L_{i,1}$ and $L_{i,2}$. The beam propagation, for better understanding, were divided into n+2 steps. The first n+1 steps were regarded as the beam expanding processes, in which the laser beam passes through every spatial filter SF_i (from SF_0 to SF_n) with $(x_i, \theta_i)'$, while in the last step, the laser beam was focalized onto the pellet by the focusing lens L_{Tar}.

Because of ambient disturbances, the lenses vibrated back and forth near their equilibrium positions, which affect the beam positioning stability. Considering the (i+1)th step, the laser beam entered SF_i with $(x_i, \theta_i)'$, passed through two vibrating convex lenses $L_{i,1}$ and $L_{i,2}$ with their vibrating displacement $a_{i,1}$ and $a_{i,2}$, respectively, and then entered the next spatial filter SF_{i+1} with $(x_{i+1}, \theta_{i+1})'$ after a propagation distance of l_i. According to Ref. [5], the relationship between $(x_i, \theta_i)'$ and $(x_{i+1}, \theta_{i+1})'$ could be described as follows:

$$\begin{pmatrix} x_{i+1} \\ \theta_{i+1} \\ 1 \end{pmatrix} = \begin{pmatrix} -m_i & k_i & p_i \\ 0 & -\dfrac{1}{m_i} & g_i \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x_i \\ \theta_i \\ 1 \end{pmatrix}, \quad (1)$$

$$m_i = \frac{f_{i,2}}{f_{i,1}}, \quad (2)$$

$$k_i = f_{i,1} + f_{i,2} - \frac{l_i}{m_i}, \quad (3)$$

$$p_i = \left(1 + m_i + \frac{l_i}{f_{i,2}}\right) a_{i,1} - \frac{l_i}{f_{i,2}} a_{i,2}, \quad (4)$$

$$g_i = \frac{a_{i,1} - a_{i,2}}{f_{i,2}}, \quad (5)$$

where $f_{i,1}$ and $f_{i,2}$ are the focal lengths of $L_{i,1}$ and $L_{i,2}$, respectively; m_i is the beam expanding ratio; and p_i and g_i are the vibrating effects of $L_{i,1}$ and $L_{i,2}$ on the beam

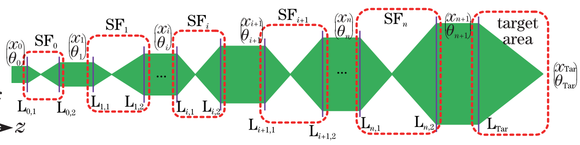

Fig. 1. Schematic of the optical system in the ICF apparatus.

tolerances of displacement and angle from SF_i to SF_{i+1}, respectively.

Furthermore, when the number of spatial filters was more than two, the relationship between the incident beam of the first spatial filter SF_0 $(x_0, \theta_0)'$ and the incident beam of the focusing lens L_{Tar}, $(x_{n+1}, \theta_{n+1})'$ was as follows:

$$\begin{pmatrix} x_{n+1} \\ \theta_{n+1} \\ 1 \end{pmatrix} = \begin{pmatrix} -m_n & k_n & p_n \\ 0 & -\dfrac{1}{m_n} & g_n \\ 0 & 0 & 1 \end{pmatrix} \cdots \begin{pmatrix} -m_i & k_i & p_i \\ 0 & -\dfrac{1}{m_i} & g_i \\ 0 & 0 & 1 \end{pmatrix} \cdots \begin{pmatrix} -m_0 & k_0 & p_0 \\ 0 & -\dfrac{1}{m_0} & g_0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x_0 \\ \theta_0 \\ 1 \end{pmatrix} = [B_n] \begin{pmatrix} x_0 \\ \theta_0 \\ 1 \end{pmatrix}, \tag{6}$$

$$B_n = \begin{pmatrix} (-1)^{n+1} \prod_{i=0}^{n} m_i & B_{n12} & B_{n13} \\ 0 & \dfrac{(-1)^{n+1}}{\prod_{i=0}^{n} m_i} & B_{n23} \\ 0 & 0 & 1 \end{pmatrix}, \tag{7}$$

$$B_{n13} = \sum_{i=0}^{n} (-1)^{n-i} \left(\prod_{j=i+1}^{n+1} m_j \right) p_i + \sum_{i=0}^{n-1} (-1)^{n+1-i} \left(\prod_{j=i+2}^{n+1} m_j \right) k_{i+1} g_i - \frac{k_n}{m_{n-1}} g_{n-2} + \sum_{i=0}^{n-3} \left((-1)^{n+1-i} \left(\sum_{j=i+1}^{n-1} \frac{\prod_{k=j+2}^{n+1} m_k}{\prod_{k=i+1}^{j} m_k} k_{j+1} \right) \right) g_i, \tag{8}$$

$$B_{n23} = \sum_{i=0}^{n} \frac{(-1)^{n-i} g_i}{\prod_{j=i+1}^{n+1} m_j}, \tag{9}$$

$$B_{n12} = (-1)^n \left(\left(\prod_{i=1}^{n} m_i \right) k_0 + \sum_{i=1}^{n} \frac{\prod_{j=i+1}^{n+1} m_j}{\prod_{j=0}^{i-1} m_j} k_i \right), \tag{10}$$

where $\boldsymbol{B}_n$ is the optical transfer matrix from the incident beam of SF_0 to that of L_{Tar} after passing through SF_0 to SF_n in succession. To simplify the expression, m_{n+1} is defined as 1 when $n+1$ spatial filters were considered.

The laser beam was focalized on the pellet in the focus of L_{Tar}, satisfying the following:

$$\begin{pmatrix} x_{Out} \\ \theta_{Out} \\ 1 \end{pmatrix} = CB_n \begin{pmatrix} x_0 \\ \theta_0 \\ 1 \end{pmatrix}, \tag{11}$$

$$C = \begin{pmatrix} 0 & f_T & a_T \\ -\dfrac{1}{f_T} & 1 & \dfrac{a_T}{f_T} \\ 0 & 0 & 1 \end{pmatrix}. \tag{12}$$

Here, $(x_{Out}, \theta_{Out})'$ is the laser beam information focalized on the pellet; $\boldsymbol{C}$ is the optical transfer matrix from the incident beam of L_{Tar} to the focus of L_{Tar}; f_T is the focal length of L_{Tar}, and a_T is the vibrating displacement of L_{Tar}.

Combining Eqs. (7) to (12), the position of the beam on the focal plane can be deduced as follows:

$$x_{Out} = \frac{(-1)^{n+1}}{\prod_{i=0}^{n} m_i} f_T \theta_0 + \sum_{i=0}^{n} (-1)^{n-i} q_i (a_{i,1} - a_{i,2}) + a_T, \tag{13}$$

$$q_i = \frac{1}{\prod_{j=i+1}^{n+1} m_j} \frac{f_T}{f_{i,2}} = \frac{1}{\prod_{j=i}^{n+1} m_j} \frac{f_T}{f_{i,1}}. \tag{14}$$

where q_i (i from 0 to n) is defined as the displacement weighting factor of the vibrations of SF_i transmitting to the pellet.

Equation (14) shows that the effects of the vibrating lenses in the spatial filters on the beam positioning stability of the pellet are:

(i) proportional to the vibrating displacement of the vibrating lens;

(ii) proportional to the focal length of the focusing lens;

(iii) inverse to the focal length of the vibrating lens;

(iv) inverse to the beam magnification from the vibrating lens to the focusing lens.

For different disturbing sources, the motion of the lenses could be different, such as vibrating in simple harmonic motion or in random motion. However, in an ICF apparatus, the beam was affected by optics, hence the beam positioning error on the pellet could be described in normal distribution[6]. In such case, the variance of the beam positioning error is the sum of the variances of every vibrating lens contributed to the beam positioning on the pellet. According to Eq. (13), the variance of the beam positioning error could be written as follows:

$$\Delta_{Out}^2 = \sum_{i=0}^{n} q_i^2 \left(\Delta_{i,1}^2 + \Delta_{i,2}^2 \right) + \Delta_T^2, \tag{15}$$

where $\Delta_{i,1}^2$ and $\Delta_{i,2}^2$ are the displacement variances of the first and second lenses in SF_i, respectively, and Δ_T^2 is the displacement variance of the focusing lens.

The additional beam in the SG-II facility had nine spatial filters ranking from SF_0 to SF_8, where SF_0 to SF_5 are in the pre-amplify zone and SF_6 to SF_8 are in the main amplify zone. The optical parameters of the beam and the displacement weighting factors of every vibrating spatial filter are listed in Table 1. The values of

q_i^2, which stand for the weighting factors of the variances of the vibrating spatial filters transmitting to the pellet, are illustrated in Fig. 2.

Figure 2 indicates that:

(i) the vibrations of the spatial filters in the pre-amplify zone had very little effects on the disturbance of the beam positioning stability to the pellet because of the large beam magnification to the focusing lens;

(ii) the vibrations of the spatial filters in the main amplify zone dominated the beam positioning stability to the pellet because of their small magnification to the focusing lens;

(iii) the vibrations in SF_7 had the largest weighting factor to the beam positioning stability.

Therefore, to enhance the beam positioning stability on the pellet, the vibrations of the spatial filters in the main amplify zone should be analyzed. Moreover, the spatial filter supportings in the main amplify zone should be optimized to reduce the disturbances to the spatial filters. As the supportings were trusses made of steel, the vibrations transmitted to the optics in the spatial filters were designed to be reduced by increasing the damping ratios of the supportings[6] using tuned mass dampers, viscoelastic materials, and other composite materials such as steel trusses filled with cement[4]. To prevent the addition of error with other beams, the spatial filters of other beams were bounded together in the SG-II facility, as illustrated in Fig. 3, and some components were isolated with other structures to prevent vibration transmission, as shown in Fig. 4.

Table 1. Optical Parameters and Calculated Displacement Weighting Factors of the Additional Beam in the SG-II Facility

Spatial Filter	Focal Length $f_{i,2}$ (m)	Beam Expanded Ratio m_i	Displacement Weighting Factor q_i
SF_0	1.0000	2.000	0.0061
SF_1	1.9559	2.455	0.0076
SF_2	1.8600	3.014	0.0241
SF_3	2.3825	2.960	0.0556
SF_4	1.9971	2.000	0.1327
SF_5	4.0808	1.500	0.0974
SF_6	4.8643	2.120	0.1733
SF_7	5.6547	1.730	0.2579
SF_8	8.4876	1.080	0.1856

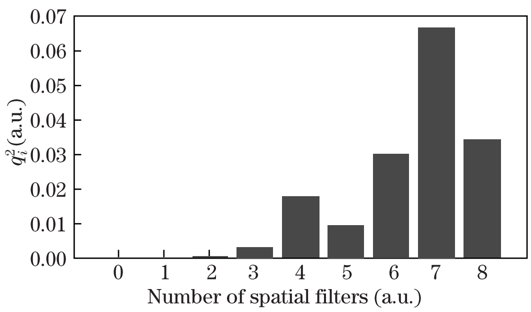

Fig. 2. Weighting factors of the variances of the vibrating spatial filters transmitted to the focal spot.

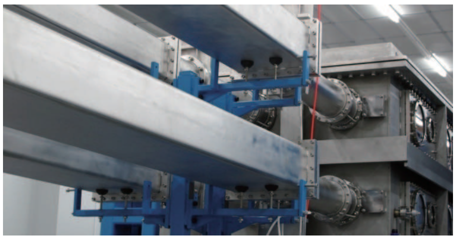

Fig. 3. Four spatial filters were bounded to prevent error addition.

Fig. 4. Some components are isolated with other structures to prevent vibration transmission.

In conclusion, the relationship between the optical parameters and the sensitivities on vibration is expressed. The sensitive components can be determined and their vibrations can be decreased to enhance the beam positioning stability efficiently. This can also be referenced in the optical design to lower the vibration sensitivity.

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