A laser beam's automatic alignment system based on the imaging properties of multiple spatial filters

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ABSTRACT

Large, high-power laser amplifiers use the imaging properties of multiple spatial filters. Spatial filtering has been shown to control instabilities; spatial filters preserve the transverse intensity profile of a high power beam as it propagates long distances through nonlinear elements as well. In this paper, image relaying is presented as a technique for aligning beams onto mm-sized target. On base of summarizing the preceding work on the near-field image relaying of multiple spatial filters, the far-filed image relaying is suggested firstly. The application of near-field and far-field image relaying properties of multiple spatial filters in laser beams automatic alignment system is analyzed. A geometrical optics approach and an ABCD ray matrix theory are used throughout. A reasonable and optimized scheme for automatic aligning multipass beam paths is presented. It is demonstrated on the multipass amplifier experimental system of the SG-III prototype.

Keywords: Beams, alignment, amplifier, spatial filters, lasers

1. INTRODUCTION

The inertial confinement fusion facility is the largest and most complex of high-power lasers, such as the Nova laser, the National Ignition Facility, the GEKKO-XII laser of Japan, the LMJ project of France and the SG-III facility of China. These lasers, propagating from the master oscillator driver to the target, interact with more than 100 near-field (NF) optical elements and pass through several spatial filter pinholes over a distance exceeding 100 m. To ensure the accuracy of these laser systems, the beam automatic alignment system has been installed on all of them. It has become an important and absolutely necessary part of this kind of laser.

It is well known that multiple spatial filters can sharply minimize nonlinear effects in high-power laser amplifiers, based on Hunt et al.'s considerations.[1,2] This is accomplished by employing both the normal filtering properties as well as the imaging properties of a spatial filter. This phenomenon may be called as NF image relaying. On base of summarizing the preceding work on the NF image relaying of multiple spatial filters, the far-field (FF) image relaying is suggested firstly. The application of NF and FF image relaying properties of multiple spatial filters in laser beams automatic alignment system is analyzed. A geometrical optics approach and an ABCD ray matrix theory are used throughout. An automated, close-loop, image-relayed, laser beam alignment system is described here. Its function is to sense beam alignment errors in a laser beam system and automatically steer mirrors to maintain beams alignment. A reasonable and optimized scheme for automatic aligning multipass beam paths is presented. It is demonstrated on the multipass amplifier experimental system of the SG-III prototype.[3]

2. IMAGE RELAYING OF NF AND FF

2.1. NF image relaying

A typical NF image relaying optical system is depicted by Fig.1, which use confocal lens pairs to meet these imaging properties. The optical transfer matrix for the k th element of this system is

$$t_k^{NF} = \begin{pmatrix} A & B \\ C & D \end{pmatrix} = \begin{pmatrix} -m_k & -m_k d_k^1 - (m_k)^{-1} d_k^2 + f_k^1 + f_k^2 \\ 0 & -1/m_k \end{pmatrix}, \qquad (1)$$

where

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High-Power Lasers and Applications III, edited by Dianyuan Fan, Ken-ichi Ueda, Jongmin Lee, Proceedings of SPIE Vol. 5627 (SPIE, Bellingham, WA, 2005)
0277-786X/05/$15 · doi: 10.1117/12.577980

$$m_k = (f_k^2)/(f_k^1) \tag{2}$$

is the magnification of the lens pair. For a system requiring N lens pairs, the system transfer matrix is as follows:

$$T_N^{NF} = \prod_{k=1}^{N} t_k^{NF} . \tag{3}$$

In terms of geometrical optics, if

$$B = m_k d_k^1 + (m_k)^{-1} d_k^2 - f_k^1 - f_k^2 = 0 , \tag{4}$$

the beam profile in the plane d_k^1 will be imaged on the plane d_{k+1}^1 with magnification m_k. When Eq. (4) is satisfied for all k, the beam will be repeatedly imaged or relayed throughout the optical train.[1, 2, 4, 5]

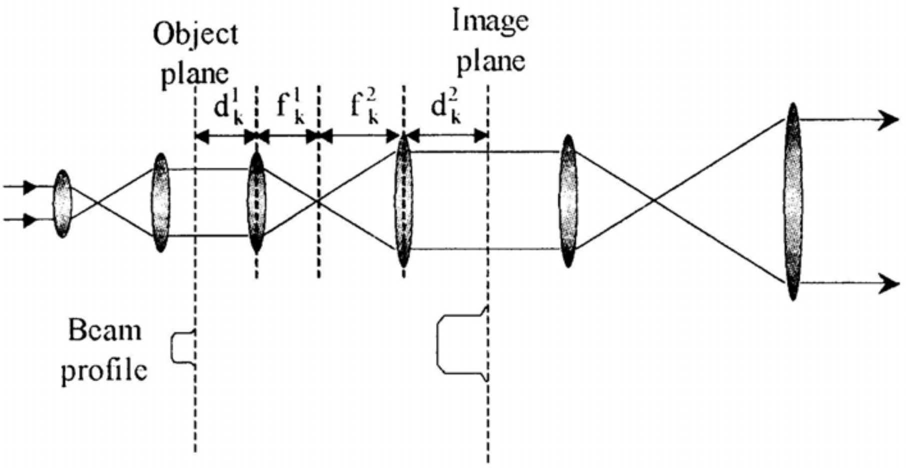

Fig.1 A typical optical relay system for NF image.

2.2. FF image relaying

Based on the research of NF image relaying, we find that multiple spatial filters have properties of FF image relaying as well. This means that the transverse intensity profile in one spatial filter's focal plane would be reimaged onto the next spatial filter's focal plane. Figure 2 depicts an optical system of FF image relaying in multiple spatial filters. We can obtain the optical transfer matrix for the k th element of this system

$$t_k^{FF} = \begin{pmatrix} A & B \\ C & D \end{pmatrix} = \begin{pmatrix} -m_k & 0 \\ (f_k^1 f_k^2)^{-1} d_k - (f_k^1)^{-1} - (f_k^2)^{-1} & -1/m_k \end{pmatrix} , \tag{5}$$

where

$$m_k = (f_k^2)/(f_k^1) \tag{6}$$

is the magnification of the lens pair. For a system requiring N lens pairs, we get the system transfer matrix

$$T_N^{FF} = \prod_{k=1}^{N} t_k^{FF} . \tag{7}$$

Since $B \equiv 0$, the beam profile in the objective plane will be imaged on the image plane with magnification m_k.

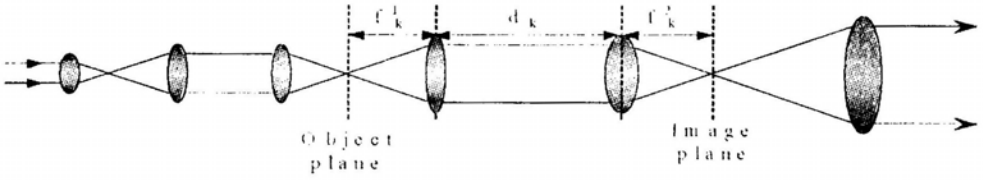

Fig.2 A typical optical relay system for FF image.

3. APPLICATIONS OF IMAGE RELAYING IN ALIGNMENT SYSTEM

3.1. Alignment system description

The objective of a beams automatic alignment system is to sense an alignment error in a high-power laser system and automatically steer mirrors preceding the detection point in a closed-loop control system to return the beam alignment to its reference location. Figure 3 is the close-loop of a typical beams automatic alignment system. The alignment errors can be introduced by the temperature's changing, the mechanical frame's distortion of mirrors, the excursion of the oscillator's output beam or any other random factors. Thus it is needed to readjust the beam paths before the new shot of the laser facility.(6-10)

The alignment errors include centering errors and pointing errors of the beams. In terms of these errors, the beams can be removed to the old location by adjusting motorized mirrors. The beam path is adjusted from head to foot until it reaches the target. The centering and pointing errors can be detected by a NF imaging detection system and a FF imaging detection system respectively. The NF and FF imaging detection systems are established according the image relaying properties.

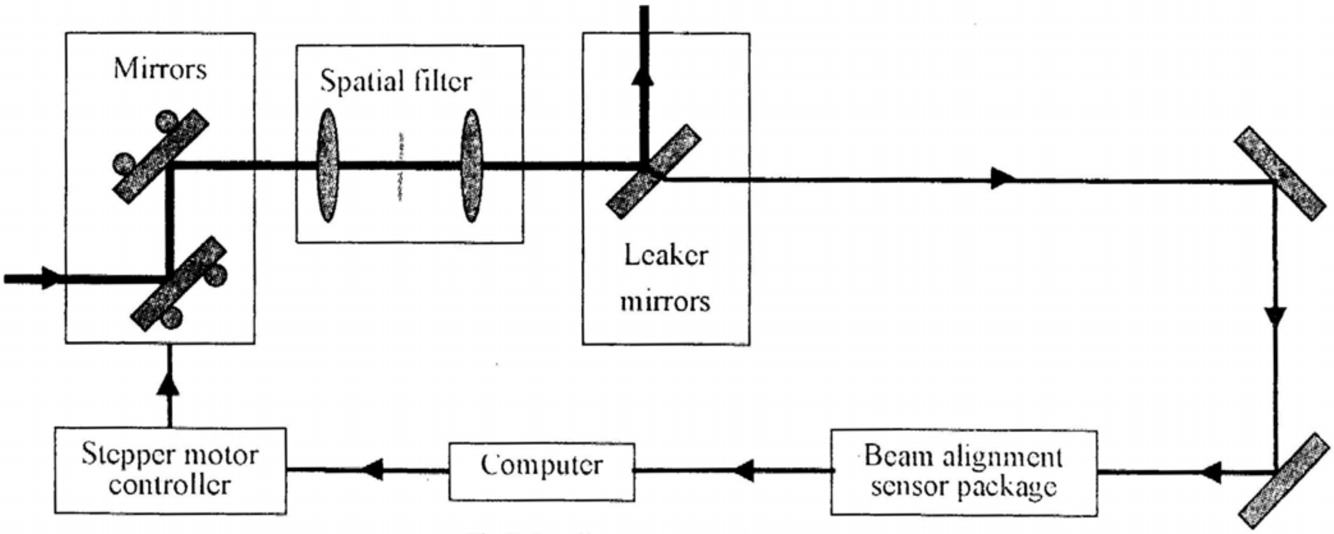

Fig.3 An alignment close-loop system.

3.2. NF imaging detection system

A single spatial filter, shown in fig. 4, is an example for explaining applications of NF image relaying in NF imaging detection system of alignment system. The collimated beam propagates from the plane A to the plane B. The A plane is an objective plane. The B plane is the image plane of the A plane and an observational plane as well, which is the detection plane of a charge coupled device (CCD).

In terms of geometrical optics, using the Eq. (1), the optical transfer matrix of this system from the plane A to the plane B is

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix} = \begin{pmatrix} -M & -Ml_1 - \frac{l_2}{M} + f_1 + f_2 \\ 0 & -1/M \end{pmatrix}, \tag{8}$$

where

$$M = f_2/f_1 \tag{9}$$

is the magnification of the lens pair. Since the plane B is the image of the plane A,

$$-Ml_1 - \frac{l_2}{M} + f_1 + f_2 = 0\,. \tag{10}$$

Thus

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix} = \begin{pmatrix} -M & 0 \\ 0 & -1/M \end{pmatrix}. \tag{11}$$

An arbitrary ray at plane A can be described as

$$\begin{pmatrix} r_A \\ \theta_A \end{pmatrix}, \tag{12}$$

where r is the ray's position at the entrance to the system. θ is the ray's angle of incidence. Thus the ray's trace at plane B is

$$\begin{pmatrix} r_B \\ \theta_B \end{pmatrix} = \begin{pmatrix} A & B \\ C & D \end{pmatrix} \begin{pmatrix} r_A \\ \theta_A \end{pmatrix} = \begin{pmatrix} -Mr_A \\ -\theta_A/M \end{pmatrix}. \tag{13}$$

It is obvious that the ray's position at plane B is linear to that of plane A. The NF CCD can detect the ray's position at plane B. So centering errors can be obtained from the NF imaging detection system in laser beams automatic alignment system.

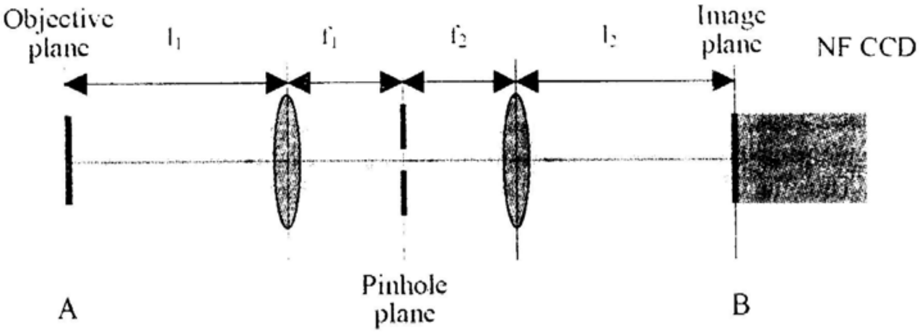

Fig.4 NF imaging detection system.

3.3. FF imaging detection system

Figure 5 is a sketch of FF imaging detection system, where the pinhole plane is imaged onto the plane B. The detection plane of the FF CCD is the image plane as well as plane B. The second lens' focal length is f_2. In the same way as the NF imaging detection system, an arbitrary ray's trace of plane A can be depicted in plane B as

$$\begin{pmatrix} r_B \\ \theta_B \end{pmatrix} = \begin{pmatrix} -\frac{f_1 l_2}{d}\theta_A \\ \frac{d}{f_1 l_2} r_A - \frac{f_1}{f_2}\theta_A - \frac{d}{l_2}\left(1 - \frac{l_1}{f_1}\right)\theta_A \end{pmatrix}. \tag{14}$$

It can be drawn from Eq. (14) that the ray's position at plane B is linear to the ray's angle of plane A. Thus pointing errors can be detected from the FF imaging detection system in laser beams automatic alignment system also.

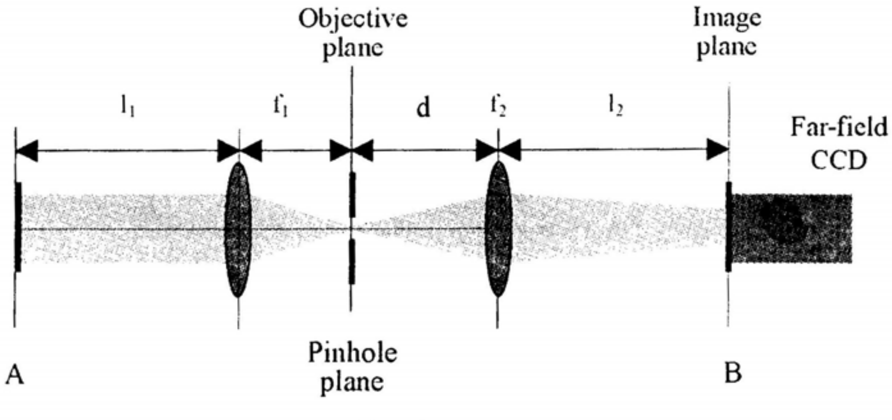

Fig.5 FF imaging detection system.

3.4. Aligning the cavity mirror

The cavity mirror (CM) is a key optical element of multipass amplifiers in aligning high-power laser facility. When beams pass back and forth several times through a multipass amplifier, they must be reflected by the same reflector (the cavity mirror). A four-pass amplifier is shown in Fig. 6 as an example, in which beams are reflected by the CM two times. So the position of the CM is fixed, and if it is not accurate, the whole beam paths cannot be correctly aligned, whatever other reflector mirrors are adjusted.

Generally, four pinholes P1, P2, P3 and P4 have the same size. In terms of FF image relaying aforementioned, the four-pass amplifier contains several pairs of relay images. First, the CM images itself in the four-pass beam path. Second, pinholes P1 and P2, located in the pinhole plane symmetrically; pinholes P3 and P4 form another pair of conjugate images as well. Third, the pinhole plane and the CM plane are located at the two focal planes of lens L, respectively.

To adjust the CM, a camera CCDFF of a FF imaging detection system is set behind imaging lens. The center of pinhole P2 is set as the FF detector CCDFF's reference. The beam light passed through pinhole P2 and is focused in the CCD photosensitive plane. At the same time, this focal plane must be the conjugate imaging plane of pinhole P2. Since pinhole P1 and P2 are conjugate, and both have the same size, pinhole P1's image must be relayed to the CCD photosensitive area of CCDFF. Thus the CM can be adjusted conveniently. A negative lens OM was inserted in front of pinhole P1 in order to make the light emanative to illuminate it. It can be examined to determine whether the image of pinhole P1 is located exactly inside pinhole P2. Figure 7(a) shows that the image of pinhole P1 was intercepted by the pinhole P2 while the CM was not correctly aligned. But the motors on CM can be driven to make the pinhole P1's image to move exactly on the center of pinhole P2. Then there was a symmetry and circular image on CCDFF, as shown in Fig. 7(b). The results indicate that the cavity mirror was correctly adjusted.[11, 12]

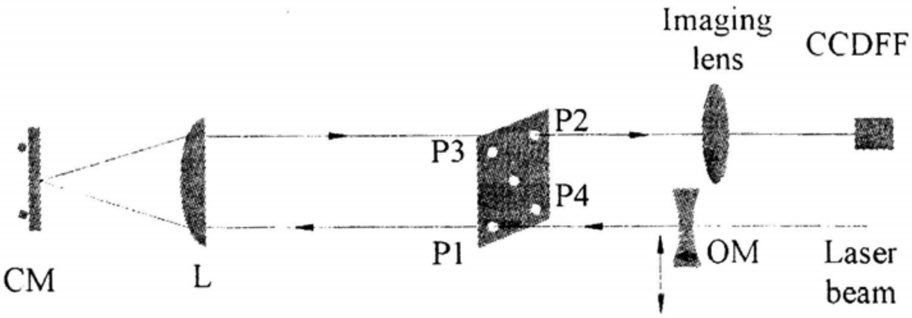

Fig.6 Alignment of the cavity mirror.

(a) (b)

Fig.7 Image (a) before and (b) after adjusting the cavity mirror.

4. SCHEME AND EXPERIMENTS

4.1. Alignment system scheme

Figure 8 depicts an experimental system of the four-pass amplifier in the SG-III prototype facility, which has half a size of the prototype facility. Based on the techniques and principles already mentioned, aimed at the multipass beam paths on the SG-III prototype laser facility, a unique scheme for automatically aligning the multipass beams was conceived. The alignment process includes 3 main steps. The cavity mirror is adjusted first. Then the first-pass and the second-pass beams are aligned. Finally, the third-pass and the fourth-pass beams are corrected. The detailed methods are as follows. The methods already mentioned in section 3.4 were used to adjust the cavity mirror CM with the help of the FF detector CCDFF12, which was set behind reflector mirror BM2. To align the first and second passes, the NF detector CCDNF12 was placed behind reflector mirror IM1, and IM1 is located at the NF image-relayed plane. The NF and FF error information was obtained through the imaging detection systems of CCDNF12 and CCDFF12. Then a computer caused mirrors IM0 and IM1 to move to steer the injected beam to pass through the pinholes P1 and P2. In adjusting the third and fourth passes, the CCDNF34 imaging detection system was set behind the reflector BM3, and the NF image-relayed plane was set at the middle of mirrors BM2 and BM3. The FF detector CCDFF34 was located behind the reflector TM1, and its reference (objective plane) was set at the pinhole plane of spatial filter-2. Thus the reversal mirrors BM2 and BM3 were adjusted so that the beam could pass through pinholes P3, P4 and the pinhole of the spatial filter-2 accurately.

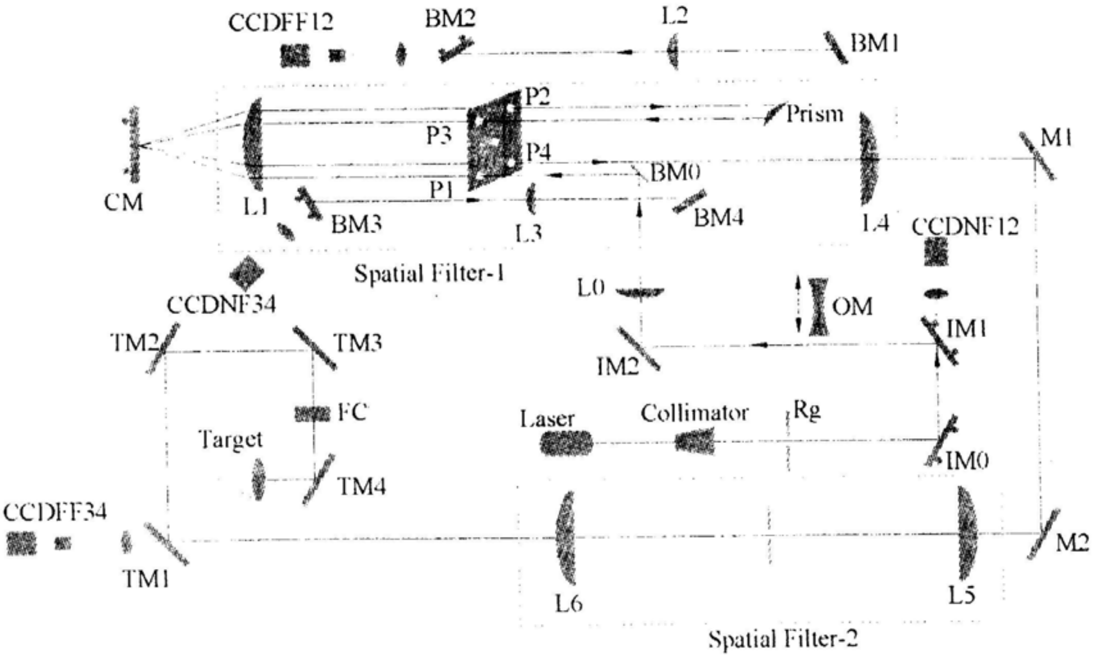

Fig.8 An alignment experimental system of the SG-III prototype facility.

4.2. Experiments and results

Experiments were performed on the alignment experiment system. The beam adjustment of the four-pass amplifier system can be accomplished in 20 minutes. The precision of the NF adjustment was less than 0.5% of the spot. The accuracy of the FF adjustment was 14.3μrad. To verify the repeatability of the beam alignment, the beam adjustment was repeated every half an hour. The results were shown as Fig 9. For these measurements, the beam was just controlled to the same CCD pixel address only 10 times. The triangle points in the figure are positions of the FF beam before alignment. The rectangular points are positions of FF reference. The circular points are positions of the FF beam after alignment. In experiments, the far field spot have a less than ideal intensity profile with its details changing in time due to gas motion in the propagation path or other factors.

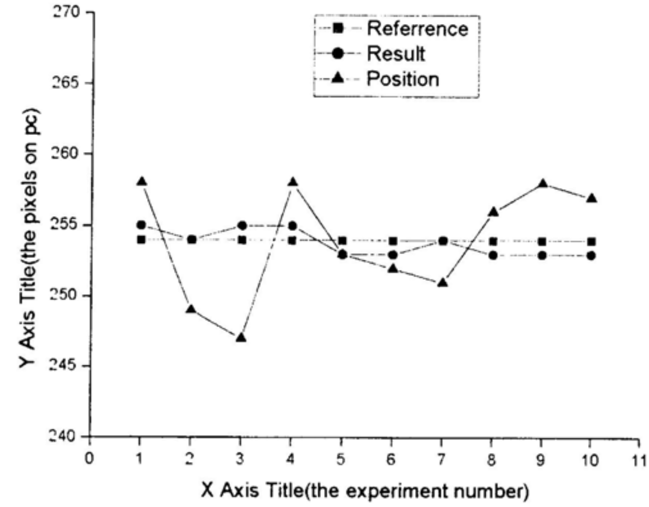

Fig.9 Experimental results of the beam alignment.

5. CONCLUSIONS

On base of summarizing the preceding work on the NF image relaying of multiple spatial filters, the FF image relaying is suggested firstly. The application of NF and FF image relaying properties of multiple spatial filters in laser beams automatic alignment system is analyzed. A geometrical optics approach and an ABCD ray matrix theory are used throughout. A reasonable and optimized scheme for automatic aligning the four-pass amplifier is presented. It is demonstrated on the four-pass amplifier experimental system of the SG-III prototype. The beam adjustment of the four-pass amplifier system can be accomplished in 20 minutes. The precision of the NF adjustment was less than 0.5% of the spot. The accuracy of the FF adjustment was 14.3μrad.

ACKNOWLEDGMENT

This work was performed under the auspices of The National High Technology Research and Development Program (863 Program). The authors would like to express thanks to the Fusion Research Center of China Academy of Engineering Physics (CAEP) for the supports in the experiments.

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