Method of Beam Steering with FWM in ICF: Compensation and Generation of a PC Beam for a Foam Target *)

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In beam steering with a phase conjugate (PC) mirror in inertial fusion energy (ICF), the path of the PC beam has to be compensated since the target moves several hundred micrometers during beam propagation. In this paper we show that compensation can be achieved by adjusting the angle between two pump beams in four-wave mixing (FWM) used as a PC mirror. The compensation angle depends on the target position along the optical axis, focal point of the final optics, and angle adjusted with FWM. For the parameter values of GEKKO XII and an accuracy of laser irradiation of ±10 µm, the compensation angle is 4.5 mrad and the margin of error for target injection is ±0.3 mm. We also show that a PC beam can be generated from the beam scattered by a foam target rotating at ∼ 43 m/s is confirmed.

Keywords: beam steering, inertial fusion energy, four-wave mixing, phase conjugate mirror, foam target

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1. Introduction

Continuous generation of neutrons from targets on a disk at 1.25 Hz has been reported [1]. The next step is irradiation of the injected target; however, precise laser irradiation technologies must be developed for target injection and beam steering. Presently, the injection accuracy for a polystyrene target is approximately ±10 mm at a distance of 1 m [2]. However, it is difficult to improve the accuracy to several dozen micrometers using only a target injector, so development of an appropriate beam steering technology is essential. One candidate for such a technology is use of a phase conjugate (PC) mirror.

Figure 1 shows a schematic with a PC mirror based on four-wave mixing (FWM). In using a PC mirror, probe beams irradiate the area in which the target has been injected; the energies of the probe beams must be low enough to not cause damage to the target. The scattered and/or reflected (SR) beam from the target passes through a window into the final optics. The beam is amplified and focused into the PC mirror. A PC beam, which originated from the SR beam, is generated and travels the same route because of the property of PC; the PC beam is amplified and irradiates the point at which the probe beams were scattered and/or reflected by the target. If the probe beams completely cover the margin area of target injection, then the PC beam has accurately irradiated the target. But the direction of the PC beam must be adjusted if the displacement of the target cannot be ignored. In the present design, the target is injected at ∼ 100 m/s [3], and the length of the laser system is several hundred meters. Therefore, by the time

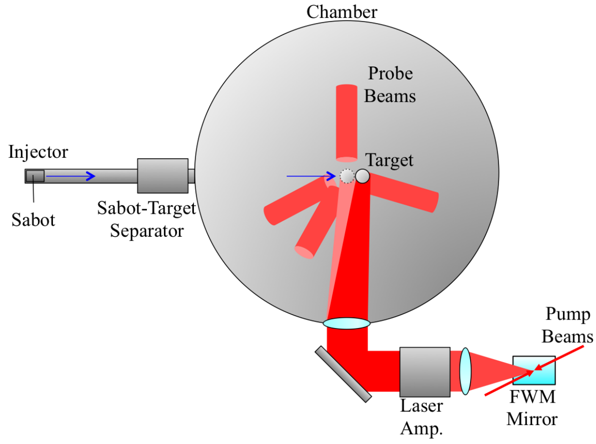

Fig. 1 Schematic of a chamber for inertial confinement fusion (ICF) fitted with a phase conjugate mirror based on FWM.

the PC beam returns to the target, the target has moved several hundred micrometers; consequently, the direction of the PC beam must be compensated. One possible solution is to insert wedged optics to adjust the direction of the PC beam. Since the beam is converted to the second or third harmonic beam and refractivity depends on the frequency of light, the direction of the converted beam would be compensated [4]. Another possible solution, which is discussed in this paper, is to compensate the PC beam using FWM as a PC mirror in a laser system in GEKKO XII.

In beam steering with a PC mirror, using an SR beam as a seed beam is important. Experiments with an actual target have not been done, although tests of compensation

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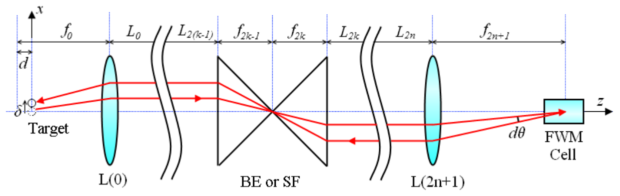

Fig. 2 Compensation of direction of the PC beam with FWM: δ, target moving distance; L(0)–L($2n+1$), lenses; $f_0 - f_{2n+1}$, focal lengths; $L_0 - L_{2n}$, distance between lenses; d, displacement of the target from focal point of L(0); dθ, compensation angle.

using a metal target have been done because metal provides high reflectivity. Here we use a foam target, which is one candidate for an actual target in ICF. We have performed experiments in which a static foam target and one rotating at ~ 43 m/s were irradiated with a PC beam.

2. Compensation of PC Beams with FWM

In FWM, two counter-propagating pump beams interact in a nonlinear material, and a seed beam irradiates the area, thereby generating a PC beam. When the two pump beams propagate in direct opposition to each other, the PC beam propagates in the direction opposite to that of the seed beam. If one pump beam is tilted at a small angle from the counter-propagating condition, the PC beam takes the same angle from the seed beam [5]. Therefore, by setting the appropriate angle between the two pump beams, compensating the direction of the PC beam is possible so as to accurately irradiate the target.

A high-power laser system includes many amplifiers, lenses, spatial filters, and optical shutters. Here, we consider a system constructed with lenses L(i) ($i = 0, 1, \ldots, 2n+1$), and, for the sake of simplicity, we ignore the influence of other optics, as shown in Fig. 2. The optical axis of the system is the z-axis, and the x-axis is normal to the z-axis. We assume the target is moving in the x-direction. The scattered beam travels through the system and is focused in the cell. The PC beam propagates in the direction that is tilted at a small angle dθ from the scattered beam and irradiates the target that has moved a distance δ.

We write the optical matrices for the initial position of the scattered beam, scattered beam propagating from the target to the cell, PC beam from the cell to the target, the PC mirror, and compensation angle with FWM as follows:

$$\mathbf{M}_{\text{ini}} = \begin{pmatrix} x_i \\ \theta \end{pmatrix},$$

$$\begin{aligned}\mathbf{M}_f &= \mathbf{M}_{f_{2n+1}}\mathbf{M}_{\text{L}(2n+1)}\mathbf{M}_{L_{2n}} \\ &\quad \cdots \mathbf{M}_{L_{2k}}\mathbf{M}_{\text{L}(2k)}\mathbf{M}_{f_{2k}}\mathbf{M}_{f_{2k-1}}\mathbf{M}_{\text{L}(2k-1)}\mathbf{M}_{L_{2k-2}} \\ &\quad \cdots \mathbf{M}_{L_0}\mathbf{M}_{\text{L}(0)}\mathbf{M}_{f_0-d},\end{aligned}$$

$$\begin{aligned}\mathbf{M}_b &= \mathbf{M}_{f0-d}\mathbf{M}_{\text{L}(0)}\mathbf{M}_{L_0} \\ &\quad \cdots \mathbf{M}_{L_{2k-2}}\mathbf{M}_{\text{L}(2k-1)}\mathbf{M}_{f_{2k-1}}\mathbf{M}_{f_{2k}}\mathbf{M}_{\text{L}(2k)}\mathbf{M}_{L_{2k}} \\ &\quad \cdots \mathbf{M}_{L_{2n}}\mathbf{M}_{\text{L}(2n+1)}\mathbf{M}_{f_{2n+1}},\end{aligned}$$

$$\mathbf{M}_{\text{PC}} = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix},$$

$$\mathbf{M}_{\text{FWM}} = \begin{pmatrix} 0 \\ d\theta \end{pmatrix},$$

where x_i is the x-position of the target, θ is the angle of the SR beam, M_{fk} is the optical matrix of the distance f_k, $\text{M}_{L(k)}$ is that of the lens L(k), and M_{Lk} and M_{f0-d} are those of the distances f_k and $f_0 - d$, respectively. With these matrices, the matrix M_T of the PC beam going back to the target is written as

$$\begin{aligned}\mathbf{M}_\text{T} &= \mathbf{M}_b\left(\mathbf{M}_{\text{PC}}\mathbf{M}_f\mathbf{M}_{\text{ini}} + \mathbf{M}_{\text{FWM}}\right) \\ &= \mathbf{M}_{\text{PC}}\mathbf{M}_{\text{ini}} + \mathbf{M}_b\mathbf{M}_{\text{FWM}}.\end{aligned} \tag{1}$$

In the first term, M_f and M_b cancel because of the property of phase conjugate, and it is written as $(x_i, -\theta)$; this means that the initial position of the target does not affect the irradiation point of the PC beam. The point only depends on the adjusted angle and optical path. From the second term in (1), the compensation distance can be written as

$$\begin{aligned}\delta &= d \cdot \text{d}\theta \cdot (-1)^n \prod_{k=0}^{n} \frac{f_{2k+1}}{f_{2k}} \\ &= d \cdot \text{d}\theta \cdot (-1)^n \frac{f_{2n+1}}{f_0} \prod_{k=1}^{n} \frac{f_{2k-1}}{f_{2k}},\end{aligned} \tag{2}$$

where d is the distance from the focal point of the final optics L(0) to the target center, f_k is the focal point of the lens L(k), and f_0 and f_{2n+1} are the focal lengths of the final optics and of the lens to focus into the FWM cell. The final term on the right side of (2) $\Pi f_{2k-1}/f_{2k}$ is the ratio of the beam waist before L(0) to that before L($2n+1$). By considering the margin of error in the laser radiation dδ, target injection dz, and compensation angle dθ', (2) can be written as

$$\begin{aligned}\delta \pm \text{d}\delta &= (d \pm \text{d}z) \cdot (\text{d}\theta \pm \text{d}\theta') \\ &\quad \cdot (-1)^n \frac{f_{2n+1}}{f_0} \prod_{k=1}^{n} \frac{f_{2k-1}}{f_{2k}}.\end{aligned} \tag{3}$$

From (3), the injection accuracy is found to be

$$\text{d}z = \left(\frac{\text{d}\delta}{\delta} - \frac{\text{d}\theta'}{\text{d}\theta}\right) d. \tag{4}$$

This result shows that injection accuracy decreases as target displacement increasers, i.e., as injection speed increases, length of the optical path increases.

Table 1 shows the value of each variable in (3) for the present design of GEKKO XII and a future design. In the current design of GEKKO XII, the target radius, D_t = 1 mm, the focal length of the final optics, f_0 = 1000 mm and $\Pi f_{2k-1}/f_{2k} = 320/43$ [6]. Round-trip length of the laser system is assumed to be approximately around 300 m; i.e., δ = 100 µm because the target injection speed

Table 1 Parameters of GEKKO XII and a future design.

	D_t [mm]	δ [μm]	dδ [μm]	d [mm]	dz [mm]	dθ [mrad]	f_0/f_{2n+1}	$\Pi f_{2k-1}/f_{2k}$
GEKKO XII	1	100	10	3	0.3	4.5	1000/1000	320/43
One Design	4	100	10	12	1.2	4.2	1000/5000	10

is 100 m/s and $f_{2n+1} = 1000$ mm. The target misalignment from the focal point of the final optics d is defined by d/R [6], where R is the target radius. We use the condition that $d/R = 2 \times f$-number, where f-number is that of the final optics; since f-number = 3 and $R = 0.5$ mm, $d = 3$ mm. Using the above values, the compensation angle is founded to be dθ = 4.5 mrad. When dδ = ±10 μm, the injection accuracy is within ±0.3 mm if we ignore dθ'. The acceptable error for target injection in the z-direction is around ten times larger than the required irradiation accuracy. In the future design with D_t = 4 mm and f_0 = 5000 mm, it is assumed that δ = 100 μm, f_{2n+1} = 1000 mm, and $\Pi f_{2k-1}/f_{2k}$ = 10. Then the compensation angle would be dθ = 4.2 mrad. Since the target radius is 4 mm, d = 12 mm. Similarly, the injection accuracy is required to be within ±1.2 mm.

3. Experiments with a Foam Target

Figure 3 shows the experimental equipment for irradiation of a foam target with a PC beam that originated from an SR beam used as the seed beam. An Nd:YAG laser (λ = 1064 nm) was used as the source of radiation. The output radiation energy was around 40 mJ in pulse of 5 - 7 ns (FWHM). As the pump beam PB1, we used the beam that passed through the wedged beam splitter WBS1, polarizer, and lens L3; PB1 irradiated in the FWM cell including FC-72. By reflecting PB1, a counter-propagating pump beam PB2 was obtained. The polarization of PB2 was normal to that of PB1 since it passed through the quarter-wave plate (QWP) twice. As the probe beam, we used the beam reflected by WBS1 to irradiate the foam target; the target material was polystyrene with a diameter of 1 mm. The SR beam was collimated by L2, passed through WBS2, amplified by two laser amplifiers, passed through WBS3, and focused into the cell via L4. Calorie meters CM1, CM2, CM3, and CM4 measured the energies of PB1 reflected twice in WBS1, of the amplified SR beam, of the SR beam, and of the amplified PC beam, respectively. Some neutral density filters were arranged in front of all calorie meters.

Figure 4 shows the energies measured by CM1, CM2, and CM4 in the experiment using the static target. The intensity of the pump beam before the cell was calculated to be ~ 30 mJ, while that of the amplified SR beam before the cell and of the beam passing through the amplifiers were ~ 21 μJ and ~ 610 nJ, respectively. This includes not only the PC beam but also noises, which arises from the scat-

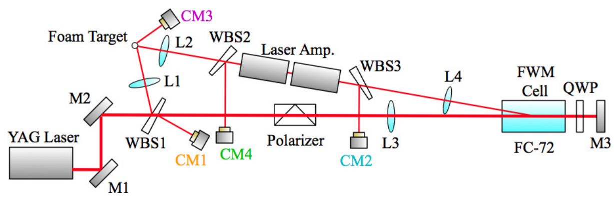

Fig. 3 Experimental Equipment; M1–3, mirrors; WBS1–3, wedged beam splitters; L1–4, lenses; QWP, quarter-wave plate; CM1–4, calorie meters.

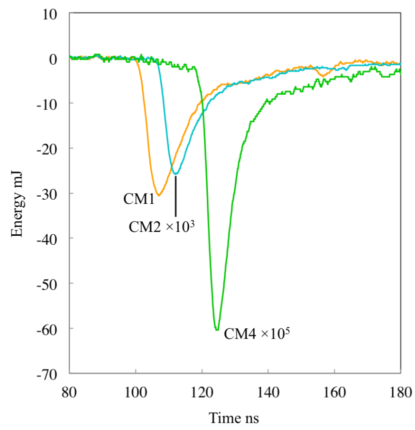

Fig. 4 Energies measured by calorie meters CM1, CM2, and CM4 in the experiment with the static target.

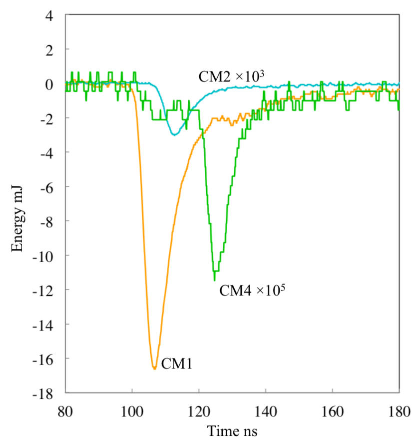

Fig. 5 Energies measured by calorie meters CM1, CM2, and CM4 in the experiment with the rotating target.

tered and/or reflected pump and seed beams that were not related to the FWM. On removing the noise, the intensity of the PC beam was ~ 300 nJ.

Figure 5 shows the energies measured in the experiment with the target rotating at ~ 43 m/s. The intensities of the pump beam, seed beam, and PC beam were ~ 17 mJ, ~ 3.0 μJ, and ~ 80 nJ, respectively.

Although irradiation of the foam target with the PC beam was not measured because the reflectivity of FWM is lower than 0.1%, it was confirmed that the FWM mirror reflected the SR beam from the foam target, which was speckled, and had about one thousand times lower intensity than the threshold of stimulated Brillouin scattering (SBS).

4. Conclusion

We have developed and tested a method for compensating a PC beam using FWM in a system constructed with lenses. With parameter values for GEKKO XII, i.e., for target radius, focal length of final optics, and beam radii, the compensation angle should be 4.5 mrad when the target moving distance is 100 μm, and the focal length of the lens to focus the SR beam into the FWM cell is 1000 mm. Assuming that an acceptable accuracy for laser irradiation is 10 μm, the accuracy for target injection should be 0.3 mm. In the future design in which the ratio of laser beams is 10, the compensation angle and acceptable accuracy of laser irradiation should be 4.2 mrad and 1.2 mm, respectively.

We have confirmed that an FWM PC mirror can generate a PC beam from the SR beam produced by a foam target; such a target is one candidate for ICF. The intensity of the amplified PC beam was approximately 300 nJ for a static target and about 80 nJ for a target rotating at ~ 43 m/s.

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