Wobbling-Beam Illumination Nonuniformity in Heavy Ion Inertial Fusion

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ABSTRACT

In an actual inertial fusion reactor, a fuel target alignment error may happen; the target alignment error induces heavy ion beam illumination non-uniformity on the target. The beam illumination non-uniformity leads a degradation of fusion energy output. On the other hand, heavy ion beam accelerator provides a capability to oscillate beam axis with a high frequency. The wobbling beams may provide a new method to reduce or smooth the beam illumination non-uniformity. In this paper, we focus on the wobbler illumination non-uniformity onto a spherical target. We found that the tolerable displacement of the target illuminated by the wobbling ion beams is about 80~90μm in a fusion reactor.

Keywords

Inertial fusion, heavy ion beam, illumination non-uniformity

1. Introduction

In direct drive method[1], laser or ion beam is used as an energy driver. Laser excels in propagation and focusing, laser energy absorption would be complicated, and laser energy absorption efficiency would be low, because the energy is absorbed at the surface of the fuel target. On the other hand, the ion beam generation and absorption efficiencies are high; heavy ion beam (HIB) deposits its energy inside of the fuel target. HIB has also other preferable characteristics of the stabile and repetitive operation of HIB accelerator and also of a precise beam axis control as well as its high efficiency (~30-40 %) of HIB generation. Therefore, it is considered that HIB would be a promising candidate of an energy driver in inertial fusion[2-5]. In this study, we employ Pb HIBs as the energy driver in order to study the beam illumination non-uniformity onto a spherical target.

In an actual inertial confinement fusion (ICF), a fuel target is irradiated by HIBs, when a fuel target is injected and aligned at the center of the fusion reactor[6]. A fuel target alignment error may happen; the target alignment error induces HIBs illumination non-uniformity on the target. The beam illumination non-uniformity leads a degradation of fusion energy output. The illumination non-uniformity allowed is less than a few percent in inertial fusion target implosion[7-10].

The HIB accelerator also has a unique feature of the HIB axis wobbling capability; The HIB axis can be oscillated or rotated with a high frequency[11]. On the other hand, the wobbling HIBs may smooth or mitigate the fuel target implosion non-uniformity[12]. In this study, we examine the wobbling-HIBs illumination non-uniformity on a direct drive fuel target, including the fuel target alignment error from the reactor center. As a result, we found that the tolerable displacement of the target illuminated by the wobbling ion beams is about 80~90μm in a fusion reactor.

2. Wobbling Beam

The HIBs illumination non-uniformity causes also the growth of Rayleigh-Taylor instability; the non-uniformity of the target implosion may prevent the fuel ignition, and causes a degradation of the fusion energy output. Therefore, it is important to reduce the instability growth and the target implosion non-uniformity.

So far, we have found that the growth of the Rayleigh-Taylor instability is mitigated well by a continuously vibrating non-uniform acceleration field with a small amplitude compared with that of the averaged acceleration[12]. The oscillating non-uniform acceleration field would be obtained by the HIBs axes oscillation[2, 11]. We used the wobbling beam as the irradiation beams. Figure 1 shows a schematic diagram for the wobbling beam. The wobbling HIBs rotate around the illumination axis as shown in Fig. 1. The rotating HIBs may provide the oscillating acceleration field with a small amplitude, and contribute to mitigate the instability growth and consequently the HIBs illumination non-uniformity. In this study, we employs the 32 wobbling HIBs to deposits their energy onto a spherical direct drive target, shown in Fig. 2.

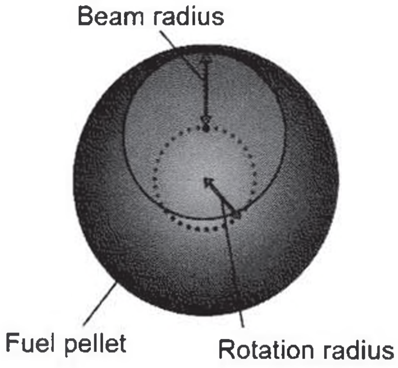

Fig. 1 Schematic diagram for Wobbling beam

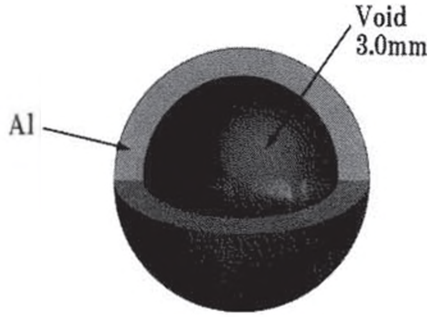

Fig. 2 Target model

3. HIB Illumination Non-uniformity

In this study, we employ lead (Pb^+) ion HIBs with the mean energy 8GeV. The HIB temperature is 100MeV and the HIB transverse distribution is the Gaussian profile. The beam radius at the entrance of a fusion reactor is 35mm and radius of a fusion reactor is 3m. Figure 2 shows the target model used in this paper. The target has a single layer structure of aluminum (Al) and its outer radius is 4.0mm.

In this study, we employ the 32 HIBs. Table 1 shows the arrangement of the 32 HIBs irradiation.

We used the Root mean square (*RMS*) as an evaluation method of the HIBs illumination non-uniformity. The formula is shown below:

$$\langle \sigma_{rms} \rangle = \sum_i w_i \sigma_i^{rms}, w_i = \frac{E_i^{Total}}{E_{Total}}$$

$$\sigma_i^{rms} = \frac{1}{\langle E \rangle_i} \sqrt{\frac{\sum_j \sum_k \left(\langle E \rangle_i - E_{i,j,k} \right)^2}{J_{mash} K_{mesh}}}$$

Here, $\langle \sigma_{rms} \rangle$ is the global rms non-uniformity, σ_i^{rms} is the rms non-uniformity on the i-th surface of deposition, w_i is the weight function, J_{mesh} and K_{mesh} are mesh numbers in θ and ϕ directions, $\langle E \rangle_i$ is the averaged energy deposited in each surface layer, E_i^{Total} is the total deposition energy in each surface layer, and E_{Total} is the total deposition

Table 1 Arrangement of the 32 HIBs irradiation

No.	θ [deg]	ϕ [deg]	No.	θ [deg]	ϕ [deg]
1	0.00	0.000	17	100.812	36.000
2	37.377	0.000	18	100.812	108.000
3	37.377	72.000	19	100.812	180.000
4	37.377	144.000	20	100.812	252.000
5	37.377	216.000	21	100.812	324.000
6	37.377	288.000	22	116.565	0.000
7	63.435	36.000	23	116.565	72.000
8	63.435	108.000	24	116.565	144.000
9	63.435	180.000	25	116.565	216.000
10	63.435	252.000	26	116.565	288.000
11	63.435	324.000	27	142.623	36.000
12	79.188	0.000	28	142.623	108.000
13	79.188	72.000	29	142.623	180.000
14	79.188	144.000	30	142.623	252.000
15	79.188	216.000	31	142.623	324.000
16	79.188	288.000	32	180.000	0.000

energy. In this study, one HIB is divided into many beamlets and the precise energy deposition is computed in the three dimensions[7, 14-17].

We also perform a spectral analysis by the spherical harmonics.

$$s_n^m = \frac{1}{4\pi}\int_0^{\pi} d\theta \int_0^{2\pi} d\phi \sin\theta E(\theta,\phi) Y_n^m(\theta,\phi)$$

Here, s_n^m is an amplitude of energy spectrum, $E(\theta,\phi)$ is the HIB deposition energy at each mesh point of a target, $Y_n^m(\theta,\phi)$ is the spherical harmonic function, and (n,m) shows the mode number.

4. Robust HIB Illumination

4.1 Irradiation of Spiral Wobbling HIBs

First we found that the HIBs illumination non-uniformity at the beginning of the wobbling HIBs irradiation. We then found that the initial imprint is reduced by spiral wobbling beams (see Fig. 3). Figure 4 shows the illumination non-uniformity history during the first few rotations. τ_{wb} is the time for one rotation of the wobbling beam axis. The non-spiral wobbling beam has the beam radius of 2.0mm and beam rotation radius of 3.0mm. For the spiral wobbling beam the beam radius changes from 3.1mm to 3.0mm at $t = 1.3\tau_{wb}$. As shown in Fig. 4, the initial imprint of the non-uniformity at the beginning of the irradiation is greatly reduced. In this study, we employ the Spiral wobbling beam for the HIBs illumination non-uniformity study.

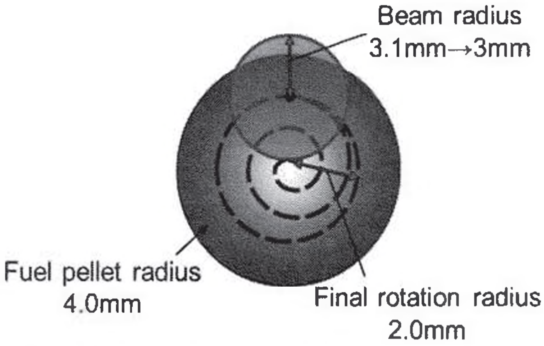

Fig. 3 Schematic diagram for spiral Wobbling beam

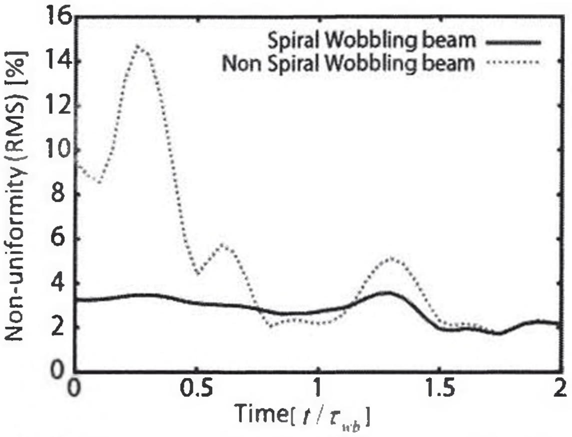

Fig. 4 Histories of the illumination non-uniformity

4.2 Spiral wobbling HIBs illumination non-uniformity

As shown in Fig. 5, dx, dy and dz are the fuel target displacements in the x, y and z-axis directions from the reactor center. The displacement of $\sqrt{dx^2 + dy^2 + dz^2}$ is also examined. Figure 6 shows the maximum illumination non-uniformity vs. the fuel target displacement. The illumination non-uniformity increases with the increase in the displacements. When the allowable maximum illumination non-uniformity is set to be less than 4.5%, the allowable dz is about 80~90μm.

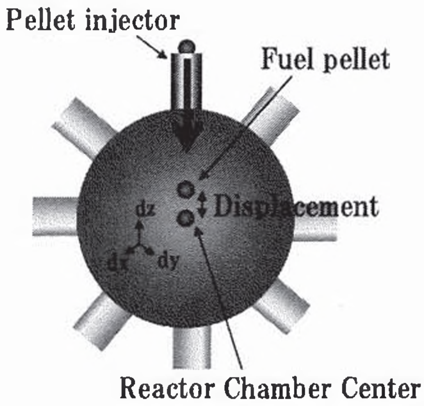

Fig. 5 Target alignment error in a reactor

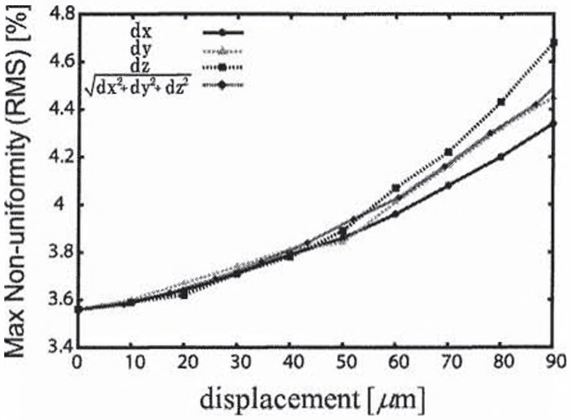

Fig. 6 Maximal non-uniformity vs. pellet displacement

Next, we examine the maximum illumination non-uniformity at the steady state after the 10 beam rotations. The HIB main pulse duration 10~20 nsec and the pre-pulse should also have the similar time duration. So the HIBs would wobble in 10 times or more. Figure 7 shows the maximum non-uniformity vs. pellet the displacement at $t = 10\tau_{wb}$. The non-uniformity becomes less than about 3~4% at the target displacement of 80∼90μm.

We also examine the HIBs illumination energy loss. Figure 8 shows the illumination energy loss vs. the pellet displacement. The HIB has a finite beam radius, and some part of HIBs ion particles do not hit the target, when the target misalignment displacement becomes large. The energy loss is about 11% $t = 10\tau_{wb}$, even when the displacement becomes 80∼90μm. The energy loss by the beam mishitting would be acceptable in ICF.

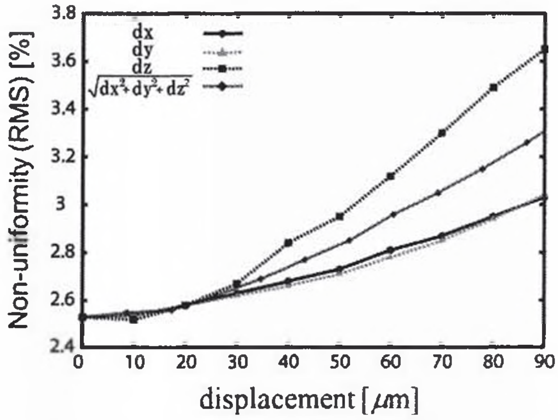

Fig. 7 non-uniformity vs. pellet displacement

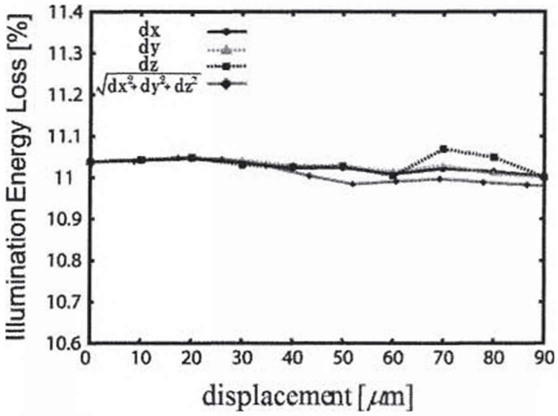

Fig. 8 Illumination energy loss vs. pellet displacement

4.3 Optimization of HIBs irradiation scheme

In this sub section, we describe the optimization of the irradiation angles of the beams to the target fuel. Figure 9 shows the schematic diagram of the definition of the angle deviation $\Delta\theta$ from the irradiation arrangement in Table 1. The irradiation arrangement of the HIBs is divided into the upper three layers and lower three layers. We change the angle of $\Delta\theta_1, \Delta\theta_2$ and $\Delta\theta_3$as shown in Fig. 9. We found that the non-uniformity is reduced well, when $\Delta\theta_1 = 0.0, \Delta\theta_2 = 0.2, \Delta\theta_3 = 0.4$ [deg]. Figure 10 shows the maximum non-uniformity for the displacement dz. By optimizing the beam illumination scheme, the HIBs illumination non-uniformity is reduced further.

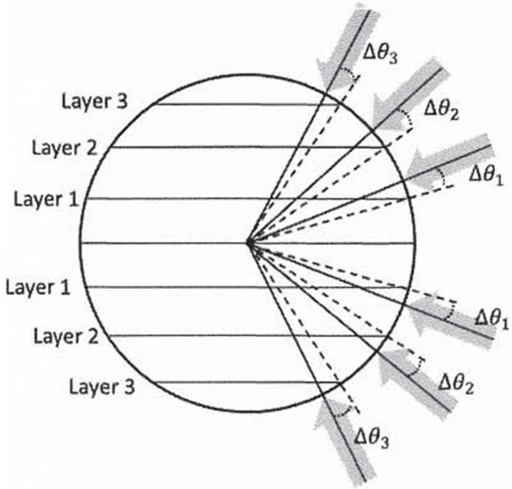

Fig. 9 Schematic diagram for the definition of $\Delta\theta$

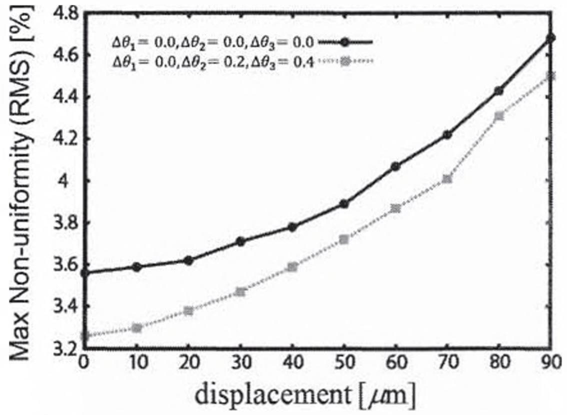

Fig. 10 Maximal non-uniformity vs. pellet displacement

4.4 Spectral evaluation

Next, we evaluate the spectrum in order to analyze the vibration of illumination non-uniformity. Figure 11 shows the histories of the illumination non-uniformity at $dz = 90\mu\mathrm{m}$. At this time, we decompose the illumination non-uniformity by the spherical harmonic spectral using the deposition energy distribution. Figure 12 shows the amplitude histories of the spherical harmonic spectrum. Figure 12 shows the spectrum mode $(n, m) = (2, 0)$. From Fig. 12, it is confirmed that the maximum value of the amplitude is reduced by the optimizing the irradiation scheme. Figure 13 presents the spectrum of the mode $(2, 0)$ amplitude in its frequency space. f_{wb} shows the wobbling HIBs rotation frequency. We confirmed the vibration frequency synchronized well with the wobbling frequency of the illumination beam.

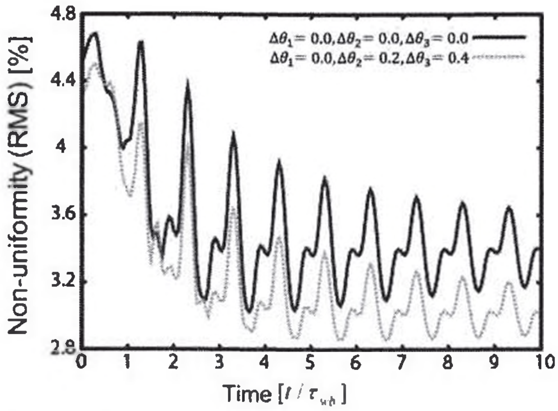

Fig. 11 Histories of the illumination non-uniformity

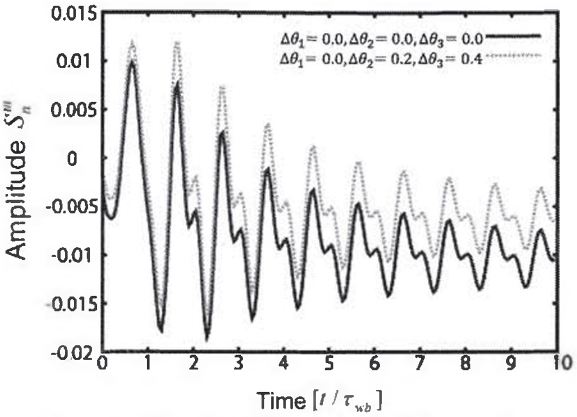

Fig. 12 Histories of the Spherical harmonic spectrum

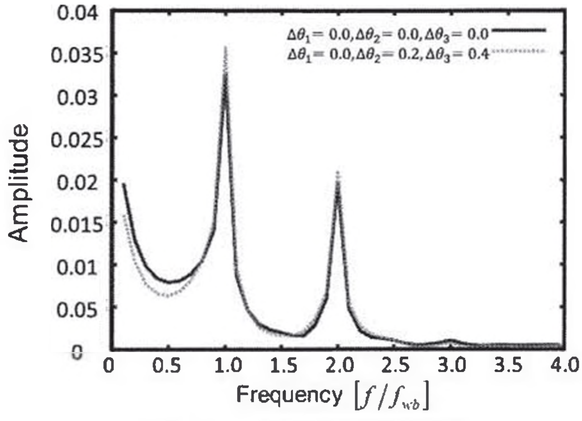

Fig. 13 Frequency spectrum

5. Conclusions

In this study, we examined the wobbling HIBs illumination non-uniformity on the fuel. The target alignment error leads the increase in the illumination non-uniformity. The tolerable displacement of the target illuminated by the spiral wobbling beams is about 80~90 μm. The illumination energy loss is not serious in ICF. In addition, by optimizing the beam irradiation scheme, the illumination non-uniformity is reduced further. We confirmed that the frequency spectrum is synchronized with the rotation frequency of the wobbling beams. The results would confirm that the wobbling HIBs illumination induce the oscillating acceleration field continuously, which may reduce the growth of Rayleigh-Taylor instability.

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