Illumination non-uniformity of spirally wobbling beam in heavy ion fusion

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Abstract. In inertial confinement fusion, the driver beam illumination non-uniformity leads to a degradation of fusion energy output. The illumination non-uniformity allowed is less than a few percent in inertial fusion target implosion. Heavy ion beam (HIB) accelerator provides a capability to oscillate a 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 the HIBs wobbling illumination scheme was optimized.

1. Introduction
In inertial confinement fusion, the driver beam illumination non-uniformity leads to a degradation of fusion energy output. Therefore, it is important to reduce the illumination non-uniformity [1]. The beam illumination non-uniformity allowed is less than a few percent in inertial fusion target implosion [2-5].

In heavy ion inertial fusion (HIF) the heavy ion beam (HIB) has preferable features, and the HIB axis is precisely controlled with a high frequency [5-9]. The HIBs illumination non-uniformity would be mitigated by the wobbling beam motion, that is, the HIB axis oscillation or rotation [5, 6]. In this study, the illumination scheme is optimized based on the spirally wobbling HIBs.

In direct drive inertial fusion, lasers or HIBs are used as an energy driver. The energy efficiency of the HIB generation is high [10-12]. In this paper we study about the illumination non-uniformity of the spirally wobbling HIBs in direct drive inertial fusion.

In HIF a fuel target is irradiated by HIBs, when the fuel target is injected and aligned at the center of the fusion reactor [13]. In an actual fusion reactor a fuel target alignment error may happen. The target alignment error induces the HIBs illumination non-uniformity.

2. HIB illumination non-uniformity
In this study, we employ (Pb⁺) ion HIBs with the mean energy of 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 the radius of a fusion reactor is 3m. We employ an Al monolayer pellet target structure with a 4.0mm external radius. The 32-HIBs positions are given as presented in [14]. The HIBs illumination non-uniformity is evaluated by the global \( \text{rms} \), including also the Bragg peak effect in the energy deposition profile in the target radial direction. In this study, one HIB is divided into many beamlets, and the precise energy deposition is computed [2, 15-16].
3. Spiral wobbling beam

So far, we have found that the growth of the Rayleigh-Taylor instability would be mitigated well by a continuously vibrating non-uniformity acceleration field with a small amplitude compared with that of the averaged acceleration [5, 6]. It is realized by using a wobbling beam. Figure 1 shows a schematic diagram for the wobbling beam. However, in our previous work [5] we found that at the initial stage of the wobbling HIBs illumination the illumination non-uniformity becomes huge and cannot be accepted for a stable fuel target implosion.

Then this problem on the initial imprint of the rotating HIBs illumination was solved by spiral wobbling HIBs as shown in Fig. 2 [6]. When the spirally wobbling beams in Fig. 2 are used, the initial imprint of the non-uniformity at the beginning of the irradiation is greatly reduced from 14% to 4%. In our study, for the spiral wobbling beam the beam radius changes from 3.1mm to 3.0mm at \( t = 1.3\tau_{wb} \). Here \( \tau_{wb} \) is the time for one rotation of the wobbling beam axis. The beam rotation radius becomes 2.0mm at \( t = 2.0\tau_{wb} \). After that, the beam rotation radius is 2.0mm. In this study, we employ the spiral wobbling beam for the HIBs illumination non-uniformity study.

Figure 3 shows the amplitude of the mode \((n, m) = (2, 0)\) vs. time, and Figure 4 presents the spectrum of the mode \((n, m) = (2, 0)\) in its frequency space. Here \((n, m)\) are the polar and azimuthal mode numbers, and \( S_{nm}^m \) is the amplitude of the spectrum, respectively. If the deposition energy distributed is perfectly spherically symmetric, the amplitude of the spectrum is 1.0 in the mode \((n, m) = (0, 0)\) in our study. For this reason, the amplitude of the mode \((n, m) = (0, 0)\) becomes large. As a result, the amplitude of spectrum mode \((n, m) = (2, 0)\) is largest and the mode \((n, m) = (2, 0)\) is dominant throughout the HIBs illumination. In Fig. 3 the time is normalized by the wobbling beam axis rotation time \( \tau_{wb} \). In Figure \( f_{wb} \) shows the wobbling HIBs rotation frequency. The result in Figure 4 demonstrates that the small non-uniformity of the HIBs energy deposition has the oscillation with the same frequency and the double frequency with the wobbling HIBs oscillation frequency of \( f_{wb} \).
4. Optimization of illumination scheme

In this section we optimize the illumination scheme for the spirally wobbling HIBs. The irradiation arrangement of the HIBs is divided into the upper and lower three layers. We changed the angle of $\Delta \theta_1$, $\Delta \theta_2$, and $\Delta \theta_3$ as shown in Fig. 5. We found that the maximum non-uniformity is reduced well, when $(\Delta \theta_1, \Delta \theta_2, \Delta \theta_3) = (0, 0.2, 0.4) \text{deg}$ or $(\Delta \theta_1, \Delta \theta_2, \Delta \theta_3) = (0.2, 0.2, 0.4) \text{deg}$. Figure 6 shows the illumination non-uniformity histories in these cases.

Next, the fuel target alignment error is evaluated in a fusion reactor. In an actual inertial confinement fusion reactor as shown in Fig. 7, the target alignment error may appear. Figure 8 shows the maximum illumination non-uniformities vs. the fuel target displacement $dz$. By optimizing the beam illumination scheme, the HIBs illumination non-uniformity is reduced further.

Finally, we evaluate the spectra in order to analyze the oscillation of the HIBs illumination non-uniformity. To this end, we decompose the illumination non-uniformity by the spherical harmonic spectral using the 3D precise HIBs deposition energy distribution [15]. Figure 9 shows the amplitude histories of the spherical harmonic spectra. In Fig. 9, it is confirmed that the oscillation amplitude is reduced by the HIBs optimized illumination scheme. Figure 10 presents the amplitude of the mode $(n, m) = (2, 0)$ in its frequency space. We found that the oscillation frequency is synchronized well with the wobbling frequency of the illumination HIBs.
5. Conclusions
In this study, we optimized the HIBs illumination scheme and evaluated a fuel target alignment error. The illumination non-uniformity is reduced by the optimization of the HIBs irradiation angles to the target fuel. In addition, we found that the frequency spectrum of the HIBs illumination non-uniformity is synchronized with the rotation frequency of the wobbling beams. This result may work to reduce also the growth of the Rayleigh-Taylor instability originated from the HIBs illumination non-uniformity [5, 6].

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Figure 9. Histories of the spherical harmonic

Figure 10. Frequency spectrum