Wobbling Heavy Ion Beam Illumination in Heavy Ion Inertial Fusion*)

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A few % wobbling-beam illumination nonuniformity is realized in heavy ion inertial confinement fusion (HIF) by a spiraling beam axis motion. So far the wobbling heavy ion beam (HIB) illumination was proposed to realize a uniform implosion in HIF. However, the initial imprint of the wobbling HIBs introduces a large unacceptable energy deposition nonuniformity. In the wobbling HIBs illumination, the illumination nonuniformity oscillates in time and space. The oscillating-HIB energy deposition may contribute to the reduction of the HIBs' illumination nonuniformity. The wobbling HIBs can be generated in HIB accelerators and the oscillating frequency may be several 100 MHz ~ 1 GHz. Three-dimensional HIBs illumination computations presented here show that the few % wobbling HIBs illumination nonuniformity oscillates successfully with the same wobbling HIBs frequency.

Keywords: heavy ion inertial fusion, wobbling heavy ion beam, heavy ion beam illumination uniformity, instability dynamic mitigation, uniform target implosion, direct drive target

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1. Inroduction

Heavy ion beams (HIB) have preferable features in inertial confinement fusion (ICF), high energy density physics, also ion cancer therapy, etc: a HIB pulse shape is controlled precisely to fit various requirements, a HIB axis is also precisely controllable, a HIB generation energy efficiency is 30 ~ 40%, a HIB particle energy deposition is almost classical, and the deposition profile is well defined. Especially HIBs deposit their main energy in a deep area of the target material.

One of important issues in ICF is the fuel target implosion uniformity; a sufficiently uniform driver energy deposition is required [1, 2]. Therefore, so far a dynamic stabilization method for the Rayleigh-Taylor (R-T) instability in the target implosion has been proposed and studied [3–5]. On the other hand, the HIB axis controllability provides a unique tool to smooth the HIB energy deposition nonuniformity, and can introduce wobbling or axis-oscillating HIBs [6,7]. The wobbling HIBs may contribute to reduce the HIBs' illumination nonuniformity. In addition, our previous work showed that the R-T instability growth can be reduced by the sinusoidally oscillating acceleration in time and space [8, 9], if the wobbling HIBs provides the oscillating acceleration required and at the same time the wobblers' illumination is sufficiently uniform. In this sense, the wobbling HIBs may have a potential to realize a uniform energy deposition.

Detailed studies of three-dimensional HIBs illumination show that HIBs illumination uniformity depends strongly on the HIBs illumination scheme [10, 11]. For the wobbling HIBs illumination (see Figs. 1 and 2), Ref. 11 showed a sufficiently small nonuniformity for circularly wobbling HIBs in a steady state, and the nonuniformity was evaluated after the wobbling HIBs energy deposition becomes steady [11]. However, the wobbling HIBs illumination is time-dependent. We found that in particular the initial HIBs illumination nonuniformity becomes large

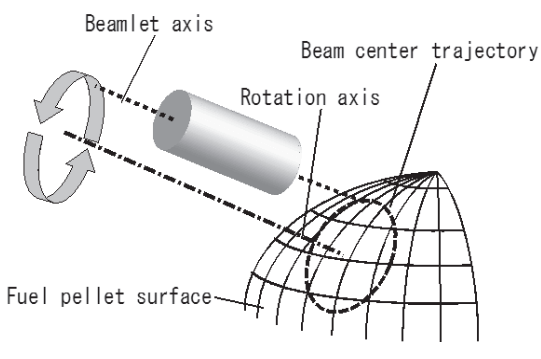

Fig. 1 The schematic diagram of wobbling HIB illumination.

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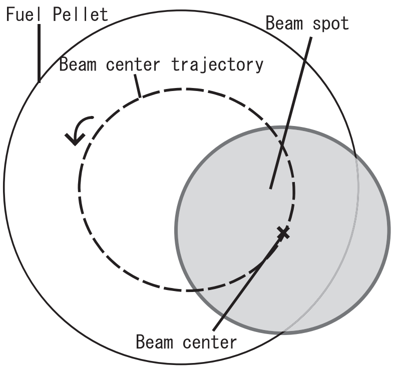

Fig. 2 A wobbling beam illumination on a direct-driven spherical target.

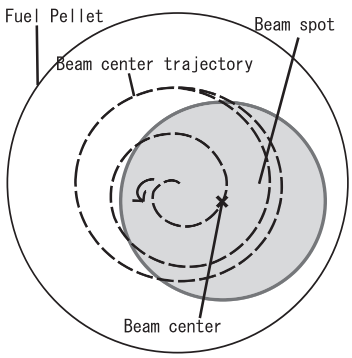

Fig. 3 Spiraling HIB. The Spiraling beam axis motion provides a sufficiently low HIBs illumination nonuniformity during the HIBs pulse duration.

and is not acceptable in ICF. In this paper we present another HIBs illumination scheme for a direct drive spherical target. In the HIBs illumination scheme proposed here, each HIB axis has a spiraling trajectory (see Fig. 3), so that the time-dependent HIBs illumination realizes a sufficiently low nonuniformity (< 3.57%) from the initial time to the HIBs pulse termination.

2. Spiraling Heavy Ion Beam Illumination

In our studies we employ Pb^+ ion HIBs with the mean particle energy of 8 GeV. The beam radius at the entrance of a reactor chamber wall is 35 mm, the reactor chamber radius is 3 m. The beam particle density distribution is the Gaussian one. The longitudinal temperature of HIB ions is 100 MeV with the Maxwell distribution. The beam transverse emittance is 3.2 mm mrad, from which the focal spot radius is obtained. The target temperature increases linearly during the time of a HIB pulse deposition from 0.025 eV to 300 eV in our study. We employ an Al monolayer pellet target structure with a 4.0 mm external radius. In our study of the HIBs illumination uniformity, we use the OK code [12], in which the detailed ion energy stopping power is computed including the beam temperature.

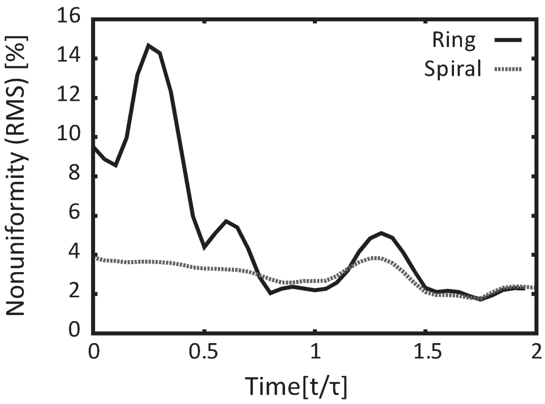

Fig. 4 Histories of energy deposition nonuniformities for the circulary moving axies (solid line) and for the spiraling HIBs. The spiraling HIB-axis motion realizes a rather low HIBs illumination nonuniformity.

The 32-HIBs rotation axes positions are given as presented in Ref. 13 [13]. The HIBs illumination nonuniformity is evaluated by the global *rms*, including also the Bragg peak effect in the energy deposition profile in the target radial direction [10]. The mode analyses are also performed to find the dominant mode of the illumination nonuniformity. The ion deposition energy is the sum of the energy deposited in target nuclei, target bound and free electrons, and target ions [10, 12, 14]. The beam radius, the total beam number and the beam rotation radius are optimized in this work. When we employed the 12 HIBs or 20 HIBs, we could not obtain a sufficient illumination uniformity [10].

When we do not employ the spiraling trajectory as shown in Fig. 2, the illumination nonuniformity history shows an unacceptable large nonuniformity during the first few rotations as presented in Fig. 4 (the solid line). In this case, the direct drive target radius is 4 mm, the energy deposition layer consists of Al, and we employ Pb^+ ion HIBs with the mean energy 8 GeV, as shown above. The HIB axis rotation radius is 2 mm and the HIB radius is 3 mm. When the spiraling HIBs are employed for the first two rotations, the HIBs illumination uniformity is drastically improved as shown in Fig. 4 (the dotted curve). In Fig. 4 the time is normalized by the wobbling beam axis rotation time τ.

Figure 5 shows the history of the spiraling HIBs illumination nonuniformity as well as the HIB particle illumination loss history. Here, we define the loss as the percentage of particles that do not hit the target. By the spiraling trajectory of the HIB axis, a sufficiently small nonuniformity is successfully realized, and a small part of the HIBs particles do not hit the target in order to obtain the illumination uniformity (see Fig. 5 (the dotted line)). Figure 6 shows an energy spectrum at $t = 1.3\,\tau$, at which time the HIBs illumination nonuniformity has a local-peak value as shown in Fig. 4 (the black line). In Fig. 6, (n, m) are the polar and azimuthal mode numbers, and S_n^m is the ampli-

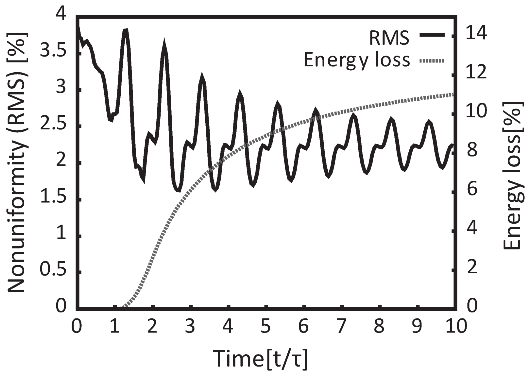

Fig. 5 Histories of the spiraling HIBs illumination nonuniformity (the solid line) and the illumination loss (the dotted line). The spiraling HIBs provide a sufficiently uniform deposition uniformity in HIF.

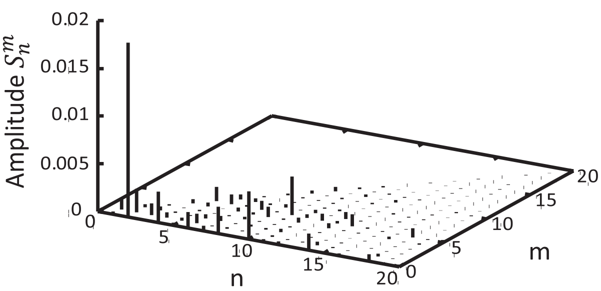

Fig. 6 The energy spectrum at $t = 1.3\,\tau$ of the spiraling HIBs. The mode $(n, m) = (2, 0)$ is dominant throughout the spiral HIBs illumination.

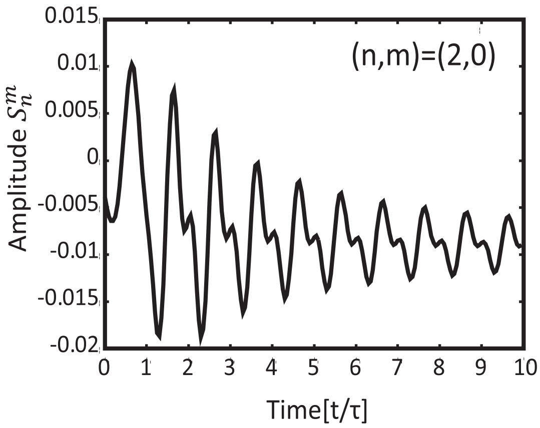

Fig. 7 The mode (2, 0) amplitude of HIBs energy deposition nonuniformity versus time.

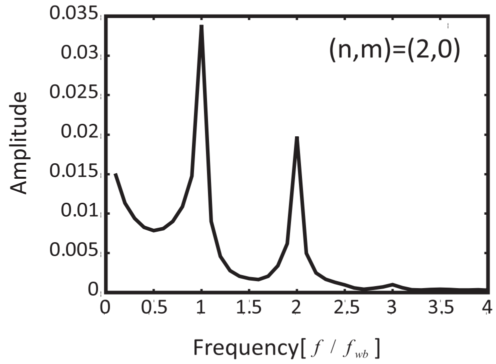

Fig. 8 Spectrum of the mode (2, 0) in its frequency space. The frequency f_{wb} is the wobbling HIB frequency. The small nonuniformity of the HIBs energy deposition has the same frequency f_{wb} of the wobblers and also the double frequency $2f_{\mathrm{wb}}$.

tude 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, nearly 1.0. In this paper the amplitude of the spectrum mode $(n, m) = (0, 0)$ is not displayed. As a result, the amplitude of spectrum mode $(n, m) = (2, 0)$ is largest in Fig. 6, and the mode $(n, m) = (2, 0)$ is dominant throughout the HIBs illumination. Figure 7 shows the amplitude of the mode (2, 0) versus time, and Fig. 8 presents the spectrum of the mode (2, 0) in its frequency space. In Fig. 8 f_{wb} shows the wobbling HIBs rotation frequency.

The result in Fig. 8 demonstrates that the small nonuniformity 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}. In addition, the total nonuniformity magnitude is suppressed less than 3.87%. The results in this paper show a possibility of a rather uniform implosion in heavy ion fusion based on the wobbling HIBs. When a perturbation inducing the implosion nonuniformity emerges during the fuel target implosion based on the origin of the deposition energy nonuniformity, the perturbation may grow from the energy deposition nonuniformity with a certain phase. In the wobbling HIBs illumination, the nonuniformity phase is defined by the wobblers' motion. The overall perturbation growth is the superposition of all the perturbations with the different initial phases but with the same wavelength. Based on these considerations, it would be pointed out that the wobbling HIBs may contribute to a fuel target uniform implosion in HIB ICF [8, 9, 15].

In the analyses presented above, the HIB radius was fixed to be 3 mm. In the wobbling HIBs illumination, the peak of the HIB energy deposition nonuniformity appears in the first few rotations at $t = 1.3\,\tau$. When the beam radius changes from 3.1 mm to 3 mm at $t = 1.3\,\tau$ during the spiral motion in the second rotations, we have an additional improvement for the HIBs illumination nonuniformity. The peak value of the nonuniformity becomes less than 3.57% (see Fig. 9), although the peak value of the nonuniformity in Fig. 5 was about 3.87%. In the results in Figs. 4-8, we have employed a fixed beam radius of 3 mm with the beam axis rotation radius of 2 mm. When we employ the spiraling beam axis motion with the fixed beam radius, in the first two rotations the spiraling beams cover the relatively

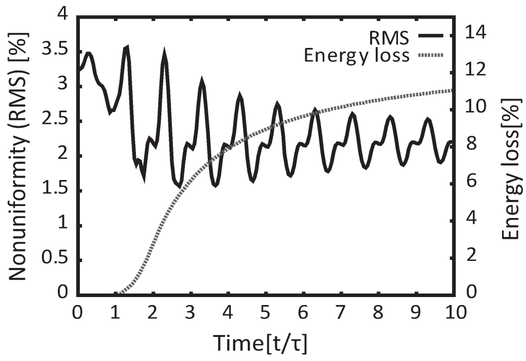

Fig. 9 Histories of the spiraling HIBs illumination nonuniformity (the solid line) and the illumination loss (the dotted line). The spiraling HIB radius changes at $t = 1.3\,\tau$ from the initial beam radius of 3.1 mm to 3.0 mm.

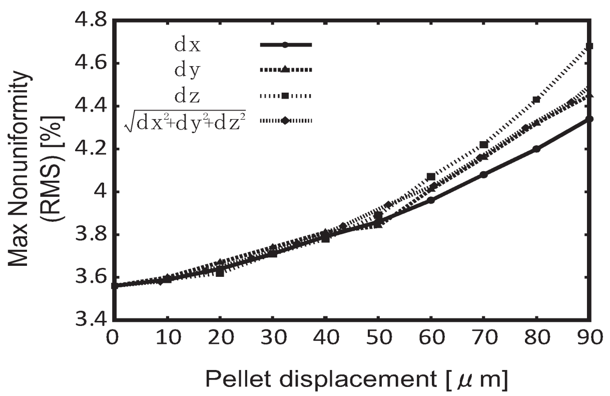

Fig. 10 The relation between the pellet displacement and the maximal rms nonuniformity in the best case, in which each HIB radius changes from 3.1 mm to 3.0 mm at $t = 1.3\,\tau$. The maximal rms nonuniformity is less than 4.5% for the pellet displacement less than about 80 μm.

smaller area of the target surface, compared with that after the initial two rotations. In addition, Figs. 4 (the dotted line) and 5 (the solid line) shows that at $t = 1.3\,\tau$ the beam illumination nonuniformity has a local peak. Therefore, the considerations suggest us to change the beam radius at $t = 1.3\,\tau$ as we employed: the larger initial beam radius of 3.1 mm is first employed and at $t = 1.3\,\tau$ the beam radius becomes smaller to 3 mm. Then we succeeded to obtain the additional improvement.

3. Robust Spiraling Heavy Ion Beam Illumination

In this section a robustness of the spiraling HIBs' illumination scheme is examined against the target alignment error in a fusion reactor. We simulate the effect of a little displacement dz as well as dx and dy on the HIB illumination nonuniformity. Here z shows the horizontal direction, and x and y present the transverse directions in a fusion reactor. Figure 10 shows the relation between the pellet displacement and the maximal *rms* nonuniformity in the best case, in which each HIB radius changes from 3.1 mm to 3.0 mm at $t = 1.3\,\tau$. The maximal *rms* nonuniformity is less than 4.5 % for the pellet displacement less than about 80 μm.

In the conventional beam illumination scheme, a fuel target displacement of 50-100 μm is tolerable [10]. The result shown in Fig. 10 means that the spiraling HIBs' illumination scheme provides the same order of the tolerable displacement with the conventional one. An enhancement of the allowable range should be studied further in the future, if required.

4. Conclusions

In this paper, we presented the HIBs illumination scheme of the spiraling HIBs, so that the HIBs illumination uniformity is drastically improved. Throughout the HIB input pulse, the beam illumination nonuniformity is kept low, that is, less than about 3.57%. The sufficiently small illumination nonuniformity is successfully realized by the wobbling HIBs onto a spherical target. The small-amplitude nonuniformity oscillation frequency is mostly the wobbling oscillation frequency and also the double of wobbling frequency. The wobbling HIBs may supply a viable uniform implosion mode in heavy ion fusion.

Acknowledgments

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