Direct-indirect hybrid mode implosion in heavy ion inertial fusion

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Direct-Indirect Hybrid Mode Implosion in Heavy Ion Inertial Fusion

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Abstract. A direct-indirect hybrid implosion mode is proposed and discussed in heavy ion beam (HIB) inertial confinement fusion (HIF) in order to release sufficient fusion energy in a robust manner. On the other hand, the HIB illumination non-uniformity depends strongly on a target displacement $dz$ from the centre of a fusion reactor chamber. In a direct-driven implosion mode, $dz$ of ~20 µm was tolerable, and in an indirect-implosion mode, $dz$ of ~100 µm was allowable. In the direct-indirect mixture mode target, a low-density foam layer is inserted, and the radiation energy is confined in the foam layer. In the foam layer the radiation transport is expected to smooth the HIB illumination non-uniformity in the lateral direction. Two-dimensional implosion simulations are performed, and show that the HIB illumination non-uniformity is well smoothed in the direct-indirect hybrid-mode target. Our simulation results present that a large pellet displacement of ~ a few hundred µm is allowed in order to obtain a sufficient fusion energy output in HIF.

1. Introduction

In heavy ion beam (HIB) inertial confinement fusion (ICF), the following critically important issues have been intensively studied: ion source, accelerator physics for high current beam, beam bunching, HIB transport in a reactor, HIB target interaction, stopping power, high-energy density matter physics, and so on [1-10]. In fuel target implosion, ICF has two ways of implosion schemes, which are indirect-driven [3, 4, 11, 12] scheme and direct-driven [13, 14] implosion scheme. Each implosion scheme has merits and demerits. The indirect-driven scheme may be robust against the beam non-uniformity and a beam number employed is low compared with that in the direct-driven scheme, though each HIB should carry a larger current and a target structure may be complicated and expensive relatively. The direct-driven pellet structure may be simple, though the scheme may be sensitive to the HIB illumination non-uniformity. In this paper, a direct-indirect mixture implosion mode is proposed and discussed in HIB ICF (HIF) in order to release sufficient fusion energy in a robust manner.

On the other hand, a pellet displacement from a reactor chamber centre influences the non-uniform implosion and may lead to a gain reduction. In this paper, we analyze a robustness of the direct-indirect mixture target implosion.

A target energy gain required for energy production in ICF can be evaluated by a reactor-energy balance. A driver pulse delivers an energy $E_d$ to a target, which releases a fusion energy $E_{\text{fus}}$. The energy gain is $G = E_{\text{fus}} / E_d$. For the driver efficiency $\eta_d$ in the range of 10 ~ 33%, the condition $G = 30 ~ 100$ is required for the power production. Therefore, the minimum pellet gain required is about 30 in HIF.
2. Direct-indirect hybrid mode
In order to study the non-uniformity smoothing effect by the radiation transport effect on a pellet implosion, the target hydrodynamics code is coupled with the HIB illumination code. Figure 1 (a) shows the fuel target without a foam layer. The confined radiation energy may smooth the HIB illumination non-uniformity. Therefore, we employ a foam layer to increase the confined radiation energy at the low density region (see Figs. 1 (b) and (c)). We call this target as a direct-indirect hybrid target in this paper. The mass density of the foam layer is 0.01 times the Al solid density in this study.

Figure 1. HIF fuel targets (a) without the foam layer, (b) with the 0.5 mm-thick foam and (c) with the 1.0 mm-thick foam.

The HIB pulse consists of a foot pulse and a main pulse as shown in Fig. 2. In this case, the total HIB energy is 4.0MJ. We employ a 32-HIBs illumination system. We evaluate the beam illumination non-uniformity at the target. In HF the Bragg peak deposition area plays the most important role for a target implosion. Therefore, we employ the total relative root-mean-square (RMS) as follows:

\[
\sigma_{RMS} = \frac{1}{n_z} \sum_{i} w_i \sigma_{RMS_i}, \quad \sigma_{RMS_i} = \frac{1}{\langle E_i \rangle} \sqrt{\sum_{j} \sum_{k} (E_{ijk} - \langle E_i \rangle)^2 / n_\theta n_\phi}, \quad w_i = E_i / \langle E_i \rangle.
\]

Here, \( \sigma_{RMS} \) is the RMS non-uniformity of beam illumination and \( \sigma_{RMS_i} \) is the RMS non-uniformity on the \( i \)-th (\( r = \)constant) surface of deposition. \( w_i \) is the weight function in order to include the Bragg peak effect. \( n_\theta, n_\phi \) and \( n_z \) are mesh numbers in each direction of the spherical coordinate. \( \langle E_i \rangle \) is the mean deposition energy and \( E_i \) is the total deposition energy on the \( i \)-th surface. \( E \) is the total deposition energy. In this paper, two-dimensional (\( r-\theta \)) simulations are performed. We employ a two-dimensional Lagrangian hydrodynamic code [14]. The physical model employed in this paper is based on a two-temperature (plasma and radiation temperatures) fluid model, coupled with the HIB illumination code [10]. The target structure is designed so that all the HIB particles deposit their energy in the outer solid Al layer, in order to avoid the target fuel preheating.

Figure 2. The HIB pulse consists of the low power part (foot pulse) and the high power one (main pulse).

In the foam layer the radiation is expected to smooth the HIB illumination non-uniformity in the lateral direction. In this section, we employ the 32-HIBs illumination system. To see the radiation transport effect on the implosion non-uniformity smoothing, we compare the results for the cases with the radiation transport (ON) and without the radiation transport (OFF) for the target shown in Fig. 1 (b). Figure 3 presents the time dependence of the RMS non-uniformity of the radiation temperature at the ablation front in the cases of the radiation transport ON and OFF. In Fig. 3 we see that the implosion non-uniformity at the ablation front becomes small effectively by the main pulse in the case
of the radiation transport ON. During the main pulse, the implosion non-uniformity can be smoothed by the radiation transport effect.

Figure 3. The time histories of the RMS non-uniformity of the radiation temperature at the ablation front in the cases of the radiation transport ON and OFF.

Figures 4 present (a) the gain curve, (b) the mean $\rho R$ and (c) the maximum ion temperature versus $dz$ of the target displacement in the cases of the radiation transport ON or OFF with/without the foam, respectively. As described in Introduction, the pellet gain must be larger than 30 in order to realize an effective energy production in HIF. In our calculation results, the pellet gain is $\sim 23$ in the case of $dz = 0$ without the foam. The gain decreases dramatically, when the pellet displacement becomes larger in the case without the foam. Therefore, it may be difficult to use a fusion electric power generation system in the case without the foam. On the other hand, in the case with the foam (see Fig. 1 (b)) the pellet gain is larger than 30 up to $dz$ of about $\sim 300 \, \mu m$ pellet displacement. From these results, the radiation transport at the low density foam region plays an important role to release an effective power production in HIF. In HIF the tolerable pellet displacement $dz$ from the fusion reactor chamber center was about 20 $\mu m$ for direct-driven implosion and about 100 $\mu m$ for indirect-driven implosion, respectively [10, 15]. Our results demonstrated that the allowable $dz$ in the direct-indirect mixture drive mode in HIF is a few hundred $\mu m$.

In this study we employ the targets with the 0.5 or 1.0 mm thickness foam as shown in Figs. 1 (b) and (c). The peak conversion efficiencies of the HIB total energy to the radiation energy are $\sim 4.5 \%$ in the case of the 1.0 mm foam, $\sim 4.5 \%$ in the case of the 0.5 mm foam and $\sim 1.5 \%$ in the case without the foam. From these results, we find that the implosion mode in the case with the foam may be a hybrid of direct- and indirect-driven modes.

Figures 5 show (a) the gain curve, (b) the mean $\rho R$ and (c) the maximum ion temperature in the cases of 1.0-mm and 0.5-mm foams, respectively. We see that the required pellet gain is satisfied in the cases of 1.0-mm and 0.5-mm foams for the displacement of $dz = 0$. However, the pellet gain is small in the case of the 1.0-mm foam compared with that in the case with the 0.5-mm foam. The implosion velocity is not sufficiently high to release the DT fusion energy efficiently, because the 1.0 mm foam thickness was too thick to create a sufficient implosion driving pressure. Therefore, the pellet gain is relatively small in the case of the 1.0 mm foam. These results indicate that the foam thickness is also important to obtain a sufficient fusion energy output.

3. Conclusions

In this paper, we discussed the target implosion non-uniformity smoothing in a direct-indirect hybrid target by using the low density foam layer. In the low density foam region, the radiation energy can be confined and the implosion non-uniformity is smoothed. In our target with the foam, the direct-indirect hybrid implosion mode is realized. From our calculation results, the peak radiation conversion efficiencies are $\sim 4.5 \%$ in the case of the 1.0 mm foam, $\sim 4.5 \%$ in the case of the 0.5 mm foam and $\sim 1.5 \%$ in the case without the foam. For the 0.5-mm thickness foam case, the implosion non-uniformity is suppressed effectively and a sufficient fusion energy output is obtained in HIF. It was also found
that the direct-indirect hybrid mode target is robust against the target displacement of $dz$. Our results present that a large pellet displacement of a few hundred $\mu$m is allowed in the direct-indirect mixed target in order to obtain sufficient fusion energy output in HIF.

Figure 4. (a) The pellet gain, (b) the mean $\rho R$ and (c) the maximum ion temperature as a function of the pellet displacement $dz$ from the fusion reactor chamber center in the cases of the radiation transport ON or OFF with / without the foam.

Figure 5. Figures (a), (b) and (c) present the pellet gain, the mean $\rho R$ and the maximum ion temperature, respectively, as a function of the pellet displacement $dz$ from the chamber center in the cases of 1.0-mm and 0.5-mm foams.

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