Uniform fuel target implosion in heavy ion inertial fusion

S Kawata[1], T Karino[1], S Kondo[1], T Iinuma[1], D Barada[1], Y Y Ma[1,2] and A I Ogoyski[3]

[1]Utsunomiya University, Utsunomiya 321-8585, Japan
[2]National University of Defence Technology, Changsha, China
[3]Techinical University of Varna 9010, Varna, Bulgaria

E-mail: kwt@cc.utsunomiya-u.ac.jp

Abstract. For a steady operation of a fusion power plant the target implosion should be robust against the implosion non-uniformities. In this paper the non-uniformity mitigation mechanisms in the heavy ion beam (HIB) illumination are discussed in heavy ion inertial fusion (HIF). A density valley appears in the energy absorber, and the large-scale density valley also works as a radiation energy confinement layer, which contributes to the radiation energy smoothing for the HIB illumination non-uniformity. The large density-gradient scale, which is typically ~500μm in HIF targets, also contributes to a reduction of the Rayleigh-Taylor instability growth rate. In HIF a wobbling HIBs illumination would also reduce the Rayleigh-Taylor instability growth and to realize a uniform implosion.

1. Introduction

In inertial confinement fusion the target implosion non-uniformity is introduced by a driver beams' illumination non-uniformity, a fuel target alignment error in a fusion reactor, the target fabrication defect, et al. For a steady operation of a fusion power plant the target implosion should be robust against the implosion non-uniformities. The requirement for the implosion uniformity is stringent, and the hotspot dynamics is also essentially important. It was confirmed that the implosion uniformity should be less than a few % [1]. In this paper the non-uniformity mitigation mechanisms in the heavy ion beam (HIB) illumination are discussed in heavy ion inertial fusion (HIF) [2-5]. In HIF targets a density valley appears in the energy absorber, and the large-scale density valley also works as a radiation energy confinement layer, which contributes to a radiation energy smoothing for the HIBs illumination non-uniformity [5]. In HIF fuel targets the density gradient scale length becomes large (typically ~500μm or so), and it also contributes to a reduction of the Rayleigh-Taylor instability (RTI) growth rate. In HIF the wobbling HIBs illumination also contributes to reduce the RTI growth [2-4]. In the paper compressible-fluid computer simulations are performed to investigate the mitigation mechanism of the HIB illumination non-uniformity. In the fluid code the three-temperature model is employed to simulate the HIF target implosion and the RTI growth with the CIP (Cubic Interpolated Profile Scheme)[6]-based ALE (Arbitrary Lagrangian-Eulerian) method [7].

Figure 1 shows a typical structure for a HIF direct drive target. The HIB ions deposit their energy inside the material mainly in the Al layer in Fig.1. The HIBs deposition stopping length is long (typically ~1mm or longer) depending on a HIB particle energy and the target material. The density gradient scale length L in a HIF target is the order of ~500 micron m or so. The large scale L of the density gradient comes from the long scale length of the HIBs energy deposition in a material.

By the expression of the RTI growth rate of $\gamma \approx \sqrt{gk/(1+kL)}$ [8, 9], the RTI modes with the long wavelength $2\pi/k$ become dominant in the HIF targets. On the other hand, inside the density valley the radiation energy would be confined, and the radiation energy is transported in the lateral direction along with the density valley to smooth the HIBs energy deposition non-uniformity.

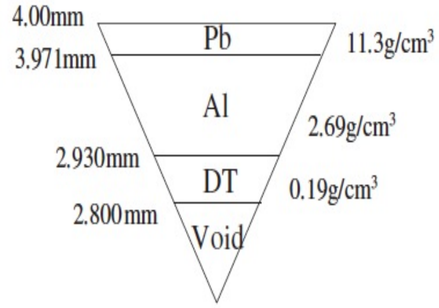

Figure 1. An example fuel target structure in heavy ion inertial fusion.

The HIB accelerator has a capability to control and rotate the HIB's axis precisely with a high frequency [10]. The wobbling HIBs would induce the dynamic mitigation of the RTI in HIF. Normally the perturbation phase is unknown so that the instability growth rate is discussed. However, if the perturbation phase is known, the instability growth can be controlled by a superposition of perturbations imposed actively: if the perturbation is induced by, for example, a driving beam axis oscillation or wobbling, the perturbation phase could be controlled and the instability growth is mitigated by the superposition of the growing perturbations [2-5]. So far the dynamic stabilization mechanism has been discussed in order to obtain a uniform compression of a fusion fuel in inertial confinement fusion. The RTI dynamic stabilization was found many years ago [9, 10] and is important in inertial fusion. It was found that the oscillation amplitude of the driving acceleration should be sufficiently large to stabilize the R-T instability [11-16].

2. Smoothing mechanisms of HIBs illumination non-uniformity

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. In this section two smoothing mechanisms are presented for the beam illumination non-uniformity in HIF.

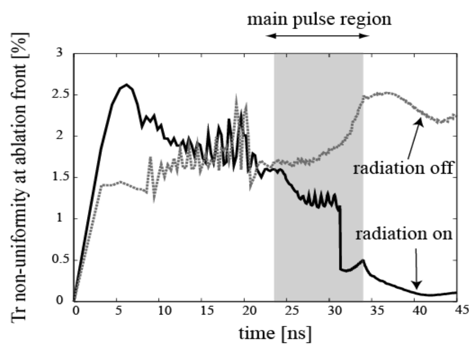

Figure 2. Histories of the non-uniformity of the radiation temperature at the ablation front in the cases of the radiation transport ON and OFF in the direct drive HIF target.

2.1. Radiation Smoothing in a HIF target implosion

The HIB ions deposit their energy in a deep layer of the energy absorber, and so a density valley appears inside the energy absorber. Even in a direct driven fuel target shown in Fig. 1, a part of the HIB energy is converted to a radiation energy confined in the density valley. The density valley plays a role to confine the radiation energy and to smooth the HIB deposition energy partly. The total HIB energy is 4.0MJ. We employ a 32-HIBs illumination system [18].

Figure 2 presents 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. In Fig. 2 we see that during the main pulse, the implosion non-uniformity is well smoothed by the radiation transport effect.

In the direct drive HIF target implosion the peak conversion efficiencies of the HIB total energy to the radiation energy are ~ 4.5%. The result means that a few hundred kJ of the radiation energy is confined in the density valley and contributes to the non-uniformity mitigation. The smoothing mechanism demonstrates that the direct drive HIF target naturally serves a direct-indirect hybrid mode of the implosion through the large density valley, which appears in the thick HIBs energy deposition layer.

2.2. *Wobbling HIBs smoothing effect of target implosion non-uniformity*

We introduce another smoothing mechanism [2-5] by the wobbling HIBs. In general a perturbation of physical quantity would be an origin of instability. Normally the perturbation phase is unknown so that the instability growth is discussed with the growth rate. However, if the perturbation phase is known, the instability growth can be controlled by a superposition of perturbations (see Fig. 3). If the perturbation is induced by, for example, a particle beam axis oscillation or wobbling [8], the perturbation phase could be controlled and the instability growth is mitigated by the superposition of the growing perturbations.

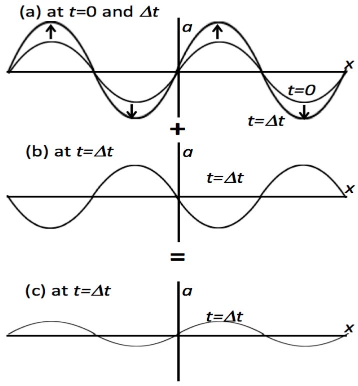

Figure 3. An ideal example concept of the dynamic mitigation. (a)At t=0 a perturbation is imposed. The initial perturbation grows with γ. (b) After Δt another perturbation, which has an inverse phase, is actively imposed, so that (c) the actual perturbation amplitude is mitigated very well after the superposition of the initial and additional perturbations.

When the instability driver wobbles uniformly in time, the imposed perturbation for a physical quantity of F at $t = \tau$ may be written as $F = \delta F e^{i\Omega\tau} e^{\gamma(t-\tau)+i\vec{k}\cdot\vec{x}}$. Here δF is the amplitude, Ω the wobbling or oscillation frequency defined actively by the driving wobbler, and $\Omega\tau$ the phase shift of superimposed perturbations. At each time t, the wobbler or the modulated driver provides a new perturbation with the phase and the amplitude actively defined by the driving wobbler itself. The superposition of the perturbations provides the actual perturbation at t as follows: $\int_0^t d\tau\ \delta F e^{i\Omega\tau} e^{\gamma(t-\tau)+i\vec{k}\cdot\vec{x}} \propto \frac{\gamma+i\Omega}{\gamma^2+\Omega^2} \delta F e^{\gamma t} e^{i\vec{k}\cdot\vec{x}}$. When $\Omega \gg \gamma$, the perturbation amplitude is reduced by the factor of ${}^{\gamma}/_{\Omega}$, compared with the pure instability growth ($\Omega = 0$) based on the energy deposition nonuniformity[11, 12]. When $\Omega \cong \gamma$, the amplitude mitigation factor is still about 50%. The result presents that the perturbation phase should oscillate with $\Omega \gtrsim \gamma$ for the effective amplitude reduction. Figure 4 shows an example simulation for RTI, which has two modes. In this example, two stratified fluids are superimposed under an acceleration of $g = g_0 + \delta g$. The density jump ratio between the two fluids is 10/3, which corresponds to the Atwood number of 0.539. In this specific case the wobbling frequency Ω is γ, the amplitude of δg is $0.1\mathrm{g}_0$, and the results shown in Figs. 4 are those at $t = 5/\gamma$. In Fig. 4(a) δg is constant and drives the RTI as usual, and in Fig. 4(b) the phase of δg is shifted or oscillates with the frequency of Ω as stated above for the dynamic instability mitigation. The RTI growth mitigation ratio is 76.0% in Fig. 4. The growth

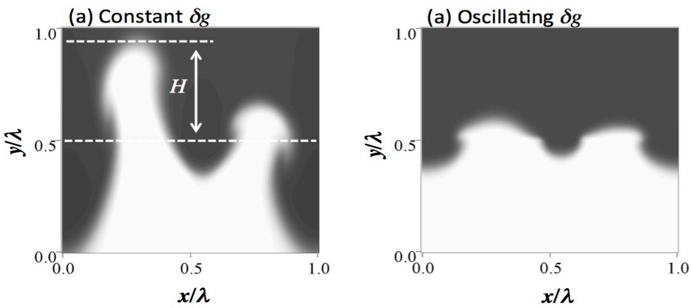

Figure 4. Example simulation results for the Rayleigh-Taylor instability (RTI) mitigation. δg is 10% of the acceleration g_0 and oscillates with the frequency of Ω=γ. The dynamic instability mitigation mechanism works well to mitigate the instability growth.

mitigation ratio is defined by (H_0 - $H_{mitigate}$)/H_0×100%. Here H is defined as shown in Fig. 4(a), H_0 shows the deviation amplitude of the two-fluid interface in the case in Fig. 4(a) without the oscillation ($\Omega = 0$), and $H_{mitigate}$ presents the deviation for the other cases with the oscillation ($\Omega \neq 0$). The example simulation results support well the effect of the dynamic mitigation mechanism.

In addition, the results presented in Ref. [18] show that the mechanism of the dynamic instability mitigation is rather robust against changes in the phase, the amplitude and the wavelength of the wobbling perturbation applied.

3. Summary

The target fuel implosion dynamics in HIF demonstrated that the density gradient scale length is rather large, about several hundred μm. In order to reduce the HIB illumination non-uniformity, two non-uniformity mitigation mechanisms were presented: the first one is the direct-indirect hybrid target, in which a part of the input HIBs energy is converted to the radiation energy in the density valley inside the target and the radiation energy contributes to the non-uniformity smoothing in HIF. The dynamic mitigation mechanism of instabilities is also introduced, and would contribute to smooth the beam driver non-uniformity. The HIB accelerator has a capability to control and rotate the HIB's axis precisely with a high frequency. The wobbling HIBs would induce the dynamic mitigation of the R-T instability in HIF. In our previous paper [5], we also found that the frequency spectrum of the HIBs illumination non-uniformity is synchronized with the rotation frequency of the wobbling beams. This result would work to reduce the growth of the R-T instability originated from the HIBs illumination non-uniformity.

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