Rayleigh-Taylor instability growth control by an oscillating acceleration in heavy ion inertial fusion

S. Kawata\textsuperscript{1}, T. Kodera\textsuperscript{1}, Y. Hisatomi\textsuperscript{1}, A. I. Ogoyski\textsuperscript{2}, S. Koseki\textsuperscript{1} and D. Barada\textsuperscript{1}

\textsuperscript{1}Utsunomiya University, Utsunomiya 321-8585, Japan
\textsuperscript{2}Varna Technical University, Varna 9010, Bulgaria

kwt@cc.utsunomiya-u.ac.jp

Abstract. Uniformity of heavy ion beam (HIB) illumination is one of key issues in HIB inertial confinement fusion (HIF) in order to compress a fuel sufficiently and release fusion energy effectively. In this paper a new mitigation method of the Rayleigh-Taylor (R-T) instability growth is presented to make a HIF target robust against a non-uniform implosion. In this study a new mitigation method of the R-T instability growth is proposed based on an oscillating perturbed acceleration, which can be realized by a rotation or oscillation of the HIB illumination axis onto a fuel pellet. The R-T instability analyses and fluid simulations demonstrate that the oscillating acceleration reduces the R-T instability growth significantly. In this paper a baseline steady acceleration $g_0$ is perturbed by a perturbed oscillating acceleration $\delta g$, which is spatially non-uniform and oscillates in time ($g_0 \gg \delta g$). An example result shows an 84\% reduction of the R-T instability growth. In the analytical work two stratified inviscid fluids are treated under the perturbed oscillating acceleration. The linear analysis shows that the R-T instability growth rate does not change from the standard expression of $\gamma$. However, the R-T instability growth is strongly affected and mitigated by the oscillating acceleration; The transverse velocity of $w$ is derived at the interface of the two stratified fluids. The R-T instability is induced by $\delta g$. The result presents that the perturbed oscillating acceleration reduces the R-T instability growth significantly depending on the magnitude of the HIB oscillation frequency.

1. Introduction

Heavy ion beam (HIB) serves a superior tool to study and to produce a high energy density state and HIB inertial fusion (HIF) plasma [1-12]. We have been pursuing a robust fuel target implosion mode by computer simulations in HIF [12-14]: to this end, research issues include HIB illumination uniformity, fuel target implosion uniformity, the Rayleigh-Taylor (R-T) instability mitigation, a non-uniformity smoothing by radiation, etc. To date a new HIB illumination scheme onto a fuel pellet was found, and it is robust against a target displacement in a fusion reactor [13]: the new robust HIB illumination scheme allows a fuel pellet displacement of 200-300 $\mu$m. It was also found that the radiation smoothing effect of the implosion non-uniformity is expected in a HIF direct-driven fuel target [15]. In addition, on the R-T instability control, a new method was also suggested in HIF by using an oscillating acceleration, which can be realized by the oscillating HIBs [12, 14, 16]. In general, fuel implosion in inertial fusion is attended by the R-T instability. Especially short wavelength modes of the R-T instability have a larger growth rate and should be mitigated by radiation transport, thermal conduction, ablation motion, etc.
In this paper we focus on the new method of the R-T instability growth control, and we found that an oscillating perturbed acceleration reduces the R-T instability growth drastically. The oscillating acceleration can be realized by oscillating HIBs illumination onto a target. The R-T instability under a non-uniform acceleration is studied by an analytical work and fluid simulations. In this paper a baseline steady acceleration \( g_0 \) is perturbed by an oscillating acceleration \( \delta g \), which is spatially non-uniform and oscillates in time ( \( g_0 \gg \delta g \) ). The HIB controllability and the well-defined HIB energy deposition may serve a well-defined perturbation of the implosion acceleration. When each HIB axis is oscillated or rotated, the wobbling HIB may serve a non-uniform and dynamically oscillating acceleration. Our analytical work and numerical computation results present that the oscillating perturbed acceleration reduces the R-T instability growth significantly. This new scenario for the R-T instability growth control can be realized by the HIB unique feature of the beam axis controllability and oscillation.

2. Rayleigh-Taylor instability under a perturbed oscillating acceleration

First we perform an analytical work to estimate an oscillating acceleration effect on the R-T instability growth:

\[
g(x,y,z,t) = g_0 + \delta g(x,y,z,t) = g_0 + g_1 f_1(x,y) \exp(-\beta z) \exp(i \Omega t). \tag{1}
\]

Here the perturbed oscillating acceleration is introduced, and we assume \( f_1(x,y) = \exp(ik_x x + ik_y y) \). In this analysis two stratified inviscid fluids are treated under the perturbed oscillating acceleration. A linear analysis shows that the R-T instability growth rate does not change from the standard expression of \( \gamma = \sqrt{\alpha g_0 k} \) for \( g_0 \gg g_1 \). Here \( \alpha \) is the Atwood number. However, the R-T instability growth is strongly affected and mitigated by the oscillating acceleration. In order to find the oscillating acceleration effect on the R-T instability growth, the transverse velocity of \( w \) is derived at the interface of the two stratified fluids as follows:

\[
w = \frac{\gamma + i \Omega}{\gamma^2 + \Omega^2} g_1 \exp(ik_x x + i k_y y)[\exp(\gamma t) - \exp(i \Omega t)]. \tag{2}
\]

The R-T instability is induced by \( g_1 \). In realistic parameter values in the HIF target implosion, \( \Omega \) can be larger than \( \gamma \); for \( \gamma \ll \Omega \), \( |w| = (1/\Omega) g_1 \exp(\gamma t) \). For \( \gamma = \Omega \), \( |w| = (1/\sqrt{2} \Omega) g_1 \exp(\gamma t) \). The result presents that the perturbed oscillating acceleration reduces the R-T instability growth significantly depending on the magnitude of \( \Omega \). The reduction ratio is \( \gamma/\Omega \). Therefore the the R-T instability growth is reduced much for \( \gamma \ll \Omega \).

This result suggests an interesting realistic scenario for the R-T instability control in HIF. First illuminating HIBs define the initial perturbation amplitude and phase of the non-uniformity introduced by HIBs themselves. The mode may have the largest perturbation amplitude and should be suppressed. Then the steerable HIB axes move slightly by the non-uniformity wavelength order to produce the oscillating \( g_1 \). The HIBs illumination non-uniformity scale size may be the order of the HIB diameter, and the HIBs' axes oscillation amplitude is also the order of the HIB radius. Therefore this scenario is rather
realistic and can be realized in a HIB accelerator system.

3. Reduction of Rayleigh-Taylor instability growth by a perturbed oscillating acceleration

In this section we perform 2-dimensional fluid simulations for the R-T instability growth control by the perturbed oscillating acceleration. Multi-HIBs illumination introduces a non-uniform acceleration. In addition, a HIB accelerator final element can give a little HIB axis oscillation or rotation. The oscillation or rotation frequency may be 100 MHz ~ a few tens GHz. The HIB axis oscillation or rotation brings the HIBs deposition energy oscillation or rotation in a fuel target energy deposition layer. Therefore, the implosion acceleration consists of a baseline steady acceleration \(g_0\) and a perturbed acceleration \(\delta g\).

Figure 1 shows a simulation setup employed in this paper. Figure 2 presents the simulation results for the R-T instability growth. In Fig. 2, \(\rho_2 : \rho_1 = 3:10\), \(g_0=1\), \(|\delta g| = 0.1\) and \(k=1\) in the normalized scale: the spatial scale is the wavelength of the R-T instability, the time scale is the inverse of \(\gamma = \sqrt{\alpha g_0 k}\). In Figs. 2 a) and b) \(\Omega = 0\), and in Figs. 2 c) and d) \(\Omega = \gamma\). For example, for \(g_0=10^{13} m/s^2\) and \(k=1/mm\), which are typical parameter values in inertial fusion, \(\Omega = 100 MHz\). The results in Fig. 2 demonstrate that the oscillating perturbed acceleration reduces the R-T instability growth significantly. The reduction ratio \((w(\Omega = 0)−w(\Omega = \gamma))/w(\Omega = 0)\) is 84.6% (see Fig. 3).

We have also checked a two-mode case: \(\exp(ikx + 2ik\Omega t)/\sqrt{2}\). Figure 4 shows another example for the R-T instability control for the two-mode case. The simulation results in Fig. 4 also show that the oscillating acceleration is very effective to mitigate the R-T instability growth as far as \(\gamma << \Omega\). The growth reduction ratio is 76.3%.

These results demonstrate that the R-T instability growth is significantly mitigated by the oscillating perturbed acceleration.

4. Discussions and Summary

The HIB wobbling oscillation frequency may reach 1 GHz ~ 100 GHz. For the R-T growth reduction presented in this paper, Eq. (2) suggests to go to the higher frequency. On the other hand, the fluid plasma should respond to the HIB oscillation to produce the oscillating acceleration \(\delta g\). When the acceleration oscillation frequency \(\Omega\) is too high, the plasma cannot respond the oscillation, so that the acceleration oscillation \(\delta g\) does not appear. The plasma response time \(\tau\) is estimated by \(\tau \sim L/C_s\). Where \(L\) should be a typical scale length of the plasma and \(C_s\) is the sound speed. Typically \(\tau\) is about \(1/1 GHz ~ 1/10 GHz\). Therefore, the preferable HIB wobbling frequency may be about 1~10 GHz or so.
This number may be achievable by the present accelerator technology. In this range of the oscillation the wobbling HIB deposited energy may serve a time-averaged overall energy deposition profile [16] with the oscillating part. This should be studied in the near future. In order to create the oscillating acceleration of $\delta g$, there may be other method in HIF: for example, each HIB can have a density modulation without the axis wobbling, and this density modulation phase can be also controlled so that $\delta g$ appears.

In this paper we proposed the new R-T instability growth control method by the oscillating perturbed acceleration. In HIF the oscillating perturbed acceleration can be realized by the HIB axis little oscillation at a HIB accelerator final element. The oscillation frequency can be 100MHz~1GHz in HIB. The analytical and numerical works demonstrate that the proposed method mitigates the R-T instability growth effectively. The results mean that a fuel target implosion non-uniformity in HIF can be significantly smoothed by the Oscillating perturbed acceleration. The oscillating acceleration mitigation of the R-T instability growth can be applied to direct-driven, indirect-driven and hybrid targets in HIF. This new scenario is based on a unique preferable feature of the HIF concept.

In general, fuel implosion in inertial fusion is attended by the R-T instability. Especially short wavelength modes of the R-T instability have a larger growth rate and should be mitigated by radiation transport, thermal conduction, ablation motion, etc and the new method by the wobbling beams proposed in this paper. The detail studies covering all modes in the R-T instability should be performed in the near future.

Acknowledgements

This work was performed under the collaboration with Dr. B.G. Logan, J. Barnard and their colleagues in HIF-VNL, U.S.A., and was partly supported by JSPS and ILE, Osaka University.

References
[1] B. G. Logan, R. O. Bangerter, D. A. Callahan, M. Tabak, M. Roth, L. J. Perkins, G. Caporaso, Fusion Science and Tech. 49 (2006) 399.
[2] B. G. Logan, F. Bieniosek, C. Celata, et al., Nucl. Instr. and Meth. A 544 (2005) 1.
[3] L. R. Prost, P. A. Seidl, F. M. Bieniosek, et al., Phys. Rev. ST Accel. Beams 8 (2005) 020101.
[4] N. A. Tahir, A. Shutov, I. V. Lomonosov, et al., High Energy Density Phys. 2 (2006) 21.
[5] N. A. Tahir, C. Deutsch, V. E. Fortov, et al., Phys. Rev. Lett. 95 (2005) 035001.
[6] S. Medin, M. Basko, M. Churazov, et al., Nucl. Instr. and Meth. A 544 (2005) 300.
[7] Y. Oguri, K. Kashiwagi, J. Kaneko, J. Hasegawa, M. Yoshida, M. Ogawa, Phys. Rev. ST Accel. Beams 8 (2005) 060401.
[8] M. Watanabe, M. Nakajima, K. Horioka, Nucl. Instr. and Meth. A 464 (2001) 440.
[9] K. Horioka, M. Nakajima, M. Watanabe, et al., Laser and Particle Beams 20 (2002) 609.
[10] S. Neff, R. Knobloch, D. H. H. Hoffmann, A. Tauschwitz, S. S. Yu, Laser Part. Beams 24 (2006) 71.
[11] C. Deutsch, G. Maynard, R. Bimbot, D. Gardes, S. Della-Negra, M. Dumail, B. Kubic, A. Richard, M. F. Rivet, A. Servaye, C. Fleuriel, A. Sanba, D. H. H. Hoffmann, K. Weyrich, H. Wahl, Nucl. Instr. and Meth. A 278 (1989) 38.
[12] S. Kawata, K. Horioka, M. Murakami, Y. Oguri, J. Hasegawa, K. Yoneda, K. Miyazawa, T. Someya, A. I. Ogoyiski, M. Seino, T. Kikuchi, T. Kawamura, M. Ogawa, Nucl. Instr. and Meth. A 577 (2007) 21.
[13] S. Miyazawa, A. I. Ogoyiski, S. Kawata, T. Someya and T. Kikuchi, Phys. Plasmas 12 (2005) 122702.
[14] S. Kawata, T. Sato, T. Teramoto, E. Bandoth, Y. Masubuchi, H. Watanabe and I. Takahashi, Laser Part. Beams 11 (1993) 757.
[15] S. Kawata, K. Miyazawa, T. Kikuchi, T. Someya, Nuclear Instr. and Meth. A 577 (2007) 332.
[16] J. Runge and B. G. Logan, Phys. Plasmas 16 (2009) 033109.