Dependence of Ablative Rayleigh–Taylor Instability on High-Z Dopant Concentration

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Abstract. We conducted two-dimensional simulations of inertial confinement fusion targets to evaluate effects of high-Z doping on implosion hydrodynamics. It was found that an ablation structure drastically changes with concentration of dopant material. We also confirmed that even a lightly-doped target can suppress Rayleigh–Taylor instability on short wavelength, while a long-wavelength perturbation is difficult to be suppressed with any dopant concentration. The high-Z doping is thus only effective for a spherical implosion with high-mode perturbations.

1. Introduction
Rayleigh–Taylor instability (RTI) at ablation front in an accelerated inertial confinement fusion (ICF) target is still a critical issue to achieve spherical implosion even though continuous efforts have been devoted to obtain inertial fusion energy. A linear growth rate of the ablative RTI $\gamma$ is obtained from the linear stability theory [1, 2]:

$$\gamma = \alpha \sqrt{\frac{kq}{1 + kL}} - \beta kv_a,$$  \hspace{1cm} (1)

where $k$ is the wavenumber of the perturbation, $g$ is the acceleration, $L$ is the density scale length, $v_a$ is the ablation velocity, and $\alpha$ and $\beta$ are the constants that depends on the ablation structure. This formula suggests the ablative RTI is suppressed especially at short wavelength thanks to mass ablation flow or finite scale length.

A concept of a high-Z doped target has been proposed to suppress the ablative RTI [3]. In the high-Z doped target, mean-free-path difference between X-rays and thermal electrons results in a double ablation structure. The linear growth rate is reduced at radiation-driven ablation (RA) front, and the ablative RTI is completely suppressed at electron-driven ablation (EA) front. However, high-Z doping may be ineffective for high-density implosion because high-Z material tends to deprive kinetic energy from the ICF target by radiation energy loss. This fact awakens us to existence of the optimum amount of high-Z doping to achieve high-density implosion.

In this study, we first conducted one-dimensional (1D) simulations of planar brominated targets to explore a transition of the ablation structure with varying the fraction of dopant. Then dispersion relation of the ablative RTI was investigated with two-dimensional (2D) simulations of
the planar targets. Finally, comparison of axisymmetric implosion simulations clarified implosion performances of the brominated fuel shells.

2. Numerical methods
We conducted numerical simulations with 2D Eulerian radiation hydrodynamics (RHD) code, RAICHO, and its axisymmetric version (one-fluid, two-temperature model) [4]. They solve the Euler equations with some energy sources with realistic equations of state (EOS) for ions and electrons. The energy sources are determined by processes of laser absorption, thermal conduction, and radiative transfer.

The governing equations are discretized with cell-centered finite volume method. The numerical flux at the cell interface is estimated by AUSM-DV scheme [5] with 2nd-order MUSCL method [6]. The hydrodynamic part is integrated by the 1st-order explicit Euler method. The thermal transfer part is integrated by the 1st-order implicit Euler method with Bi-CGSafe linear solver [7] preconditioned by incomplete LU factorization. The EOS for ions is based on the Cowan model and that for electrons is based on the Thomas–Fermi model [8]. The laser absorption of inverse-bremsstrahlung is calculated by 1D ray-tracing by neglecting the refraction of the laser rays. The thermal conduction is computed by the diffusion approximation with Spitzer–Härm conductivity [9] and the flux limiter of 0.1. The X-ray radiative transfer is formulated by the multi-group diffusion approximation with the variable Eddington factor and the collisional radiative equilibrium opacity (32 energy groups).

3. Results and discussions
3.1. Double ablation structure
We first conducted 1D simulations of the planar targets with varying the fraction of bromine. The simulation domain is described in Figure 1(a). The initial target thickness was set to 16 µm and irradiated by laser. The input laser was a flat-topped pulse with maximum intensity of $1 \times 10^{14}$ W/cm² and 0.53-µm wavelength.

Figure 2 shows the density profiles of each brominated target at 3.0 ns after the beginning of the laser irradiation. Legends indicate the fraction of bromine in composition. The peak density of the target becomes lower as the fraction of bromine increases for the lightly-doped cases (less than 0.5%). In contrast, the heavily-doped target (more than 0.5%) behaves oppositely. This phenomenon is caused by the difference of X-ray absorption between the lightly-doped region and heavily-doped region. In the case of the lightly-doped target, the self-emitted X-rays are absorbed at high-density region and depress the peak density. On the other hand, in the case of the heavily-doped target, most of X-rays are absorbed at low-density region, forming a plateau.
region, and then the peak density is kept high. Hence, there is a fraction of high-Z to minimize the peak density.

![Figure 2.](image)

**Figure 2.** Density profiles with different doping fractions at the acceleration phase \((t = 3.0 \text{ ns})\).

3.2. Ablative RTI
The dispersion relation of the ablative RTI was examined with 2D simulations of the planar targets. The initial target thickness was set to 16 µm and irradiated by laser. The laser condition was the same as the 1D cases.

Figure 3 shows the dispersion relation for the ablative RTI at the acceleration phase. The fractions appearing on the legends correspond to the targets used in GEKKO XII experiments [10]. The 0.3%-doped target reduces the linear growth rate of the ablative RTI at the short wavelength \((\approx 10 \text{ µm})\) as well as the 3.0%-doped one does since the RA front gradient of the former is gentler than that of the latter. However, the 0.3%-doped target does not suppress the ablative RTI so as the 3.0%-doped target does in the intermediate wavelength \((30 - 50 \text{ µm})\) because the ablation velocity becomes lower as the fraction of bromine decreases. Thus, the lightly-doped target is effective only for the short wavelength in the suppression of the ablative RTI.

3.3. Spherical implosion
Axisymmetric implosion simulations were conducted to evaluate implosion performances of the brominated void shells. The simulation domain is described in Figure 1(b). The initial target diameter was set to 500 µm, and the initial target thickness was 7 µm. The input laser was a flat-topped pulse with maximum power of 1.5 TW, 0.53-µm wavelength, and 2-ns pulse duration.

Figures 4 and 5 depict density contours with low-mode \((l = 6)\) perturbation and those with high-mode \((l = 32)\) perturbation, respectively. The lower-left presents the density of the non-

![Figure 3.](image)

**Figure 3.** Linear growth rates for the ablative RTI at the acceleration phase \((t = 2.4 - 3.0 \text{ ns})\).

Table 1. Maximum compression density of the brominated shells.

| \(l\) | 6   | 32  |
|-------|-----|-----|
| % of Br | 0.0 | 0.3 | 3.0 |
| 0.0  | 3.0 |
| \(\rho_{\text{max}} \text{[g/cm}^3\text{]}\) | 47.1 | 40.4 | 33.4 |
| 13.4 | 15.9 | 17.0 |
doped target at the acceleration phase (0.8 ns), the others are for the brominated targets (0.0%, 0.3%, 3.0%) at the maximum compression. Table 1 presents the maximum compression density of the brominated targets. The maximum compression density with low-mode perturbation becomes smaller with decrease of the target momentum due to the radiation loss. Furthermore, the high-Z doping cannot suppress the low-mode perturbation so much. On the other hand, in the case with high-mode perturbation, the maximum compression density becomes greater with increase of the bromine concentration. It may come from the fact that the high-Z doping spoils the nonlinearity of the ablative RTI and prevents a break of the target. As a consequence, the high-Z doping is only effective for suppression of high-mode perturbations.

4. Conclusions
We conducted two-dimensional RHD simulations to confirm the effect of high-Z doping in laser-accelerated targets. The ablation structure seems to change depending on the fraction of the high-Z dopant. A 0.3-mol% doped target can suppress Rayleigh–Taylor instability on the short wavelength. In a spherical implosion, we may conclude that the high-Z doping is only effective for high-mode perturbations.

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