Simulations of high-mode Rayleigh-Taylor growth in NIF ignition capsules

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Abstract: Near the pusher/fuel interface in the NIF indirect drive ignition capsule, the cold dense fuel can reach higher density than the material accelerating it. Unlike the outer surface where ablative stabilization is important, Rayleigh-Taylor (R-T) growth at this interface is stabilized only by the density gradient, plasma viscosity and mass diffusion. Highly resolved 2D and 3D HYDRA simulations of capsules seeded with a representative surface spectrum up to modes ~2000, with only gradient stabilization, indicate for our earlier design (“Rev 1”) a final mix width > 30 µm, resulting in >10% Be in the outer ~25% of the DT fuel. No degradation in the capsule neutron yield is observed. Simulations indicate that the R-T growth at this interface can be significantly reduced by increasing the Cu fraction in the Be ablator. This optimization is a key feature in our new designs (“Rev 2”).

1. Introduction
In the indirect drive NIF target, the innermost region of the Be ablator is shielded from the drive x-rays by outer layers of Be that are doped with varying amounts of Cu. The shielding reduces the heating of the innermost layer, keeping the density high so as to accelerate the dense DT with minimum instability growth. A profile of the density and temperature, for a “Rev 1” target as the capsule approaches peak velocity, is shown in Figure 1. The difference in the heating of the Be and the relatively transparent DT is apparent in the rapid rise in the temperature across the interface. The DT fuel closest to the interface is heated by the hotter Be through thermal conduction, causing its density to drop, in order to maintain pressure balance. Similarly, the Be closest to the interface is cooled, and its density increases.

At an imbedded interface, without ablative stabilization, and neglecting viscosity and mass diffusion, the R-T growth rate is given by \( \gamma_{RT} = \sqrt{\frac{A kg}{(1 + A k L_p)}} \) where the mode number \( k = \frac{2\pi}{\lambda} \), the Atwood number \( A = (\rho_2 - \rho_1)/(\rho_2 + \rho_1) \), and \( g \) is the acceleration. The growth rate increases for shorter wavelengths until the wavelength is small compared to the density gradient scale length, \( kL_p \gg 1 \), where it is then limited to \( \gamma_{RT} = \sqrt{g/L_p} \). For an initial perturbation at the interface describe by a power spectrum that decreases in amplitude with increasing \( k \), the dominant mode after growth will be at a wavelength comparable to the scale length. The gradient scale length for the DT and Be in the region of their interface is determined by the thermal conductivity in the two materials. For the density profile at the time shown in Figure 1, \( L_p \approx 2 \mu m \). It is important to note, however, that thermal conductivity models are uncertain in this regime (~10 g/cc, ~30 eV), and not confirmed by experiment. The effect on the density profile from multiplying the Lee-More^{3} conductivity by an
arbitrary factor of 0.3 and 3.0 is shown in Figure 1b. In 2D simulations with a perturbation at the interface, we observe a corresponding change in growth rate and final mix thickness. For the studies described below, we generally use Purgatorio conductivities.\textsuperscript{4}

Figure 1. a) Radial profile, from a HYDRA\textsuperscript{5} simulation during the implosion (14.4 ns), of the capsule density (g/cc) and 0.3 $\times$ temperature (eV); b) Variation in the profiles for 0.3 (dot), 1.0 (solid), and 3.0 (dash) times the nominal thermal conductivity (Lee-More).

2. Results
All simulations reported here are performed with HYDRA.\textsuperscript{2} To resolve the R-T growth for modes $m = 2\pi r / \lambda = 1000-2000$ requires $\sim$ 60-110 angular zones/deg, and $\sim$1000 radial zones distributed so that a resolution of $\leq 0.1 \mu m$/zone is attained at the ablation front, the DT interface, and the inner DT surface. The roughness at the surfaces of the Be capsule are specified by either a random sum of modes with amplitudes determined by a power spectrum (PS),\textsuperscript{6} or an actual measured surface from a spherical interferometer (SI) developed in collaboration with General Atomics.\textsuperscript{7}

Results from a simulation of an 18° wedge on the equator, with PS roughness on both the inner and outer surfaces of the Rev 1 (300 eV peak drive temperature) Be capsule are show in Figure 2.

Figure 2. (a) Density and Material Region (Left to right: DT, Be, Be+0.35% Cu, Be+0.7% Cu) at 14.9 ns, spatial scale in cm. (b) Perturbation peak-to-peak amplitude vs. time.
Figure 2a shows a pseudo color plot of the density in the upper half of the picture and a material region plot in the lower half, at 14.9 ns when the capsule has reached peak implosion velocity. Short wavelength (mode ~1000) perturbations are apparent at the interface between the DT and Be. The time dependent mix width at the DT:Be interface, plotted in Figure 2b, grows to ~ 30 µm. A reduction in growth rate is apparent after ~14 ns once the perturbation amplitude is comparable to the wavelength, consistent with the onset of saturation. The mass fraction of Be at a given radius vs. fractional DT fuel mass inside that radius is shown in Figure 3. For this case, the outer 30% of the fuel contains more than 10% Be by mass. This capsule ignited and burned in the simulation, producing over 11 MJ (c.f. 12 MJ “clean” 1D). The mix fraction from a simulation with a smooth Be capsule, and with roughness only on the innermost DT ice surface is also shown. In this case the perturbation grows after it is seeded at the DT:Be interface by the shock reflected from the rough ice surface (Figure 2b).

Figure 3. The mass fraction of Be at a given radius vs. fractional DT mass inside that radius, when the core temperature is 8 keV (15.2 ns), for two cases: roughness on inner and outer Be shell only; roughness on DT ice surface only.

Actual measured surfaces of Be capsules from the SI contain small, localized “defects”. Results from a 3D HYDRA simulation (4.5° × 4.5° equatorial segment, resolving up to mode ~1000) of the Rev 1 target, using measured roughness for the inner and outer Be surface, are shown in Figure 4. For this simulation, the inner surface was chosen to include a region with several > 20 nm defects to assess their effect on the mix region. For this case, the simulated mix width grows to 50 µm by peak velocity. The yield from this simulation was 12.9 MJ. The mass fraction of mixed Be is shown in Figure 5. The simulation indicates that fingers of Be will penetrate through 75% of the fuel. Note however, that the mass fraction corresponding to these fingers is dependent on the number of defects in the simulated region. From the interferometer record studied for this simulation, defects greater than 20 nm are ~ 10 × more numerous per unit solid angle in the small patch used in the simulation than in the full data record. This implies a ~ 10 × reduction in total mass fraction at a given radius for the deeply penetrated material. This will be addressed more accurately in future work.

In the “Rev 2” design (1.2 mm diameter capsule, 285 eV peak drive temperature), a higher Cu fraction is used in the doped Be layers to mitigate high mode growth, resulting in less heating of the innermost Be layer, and therefore higher Be density in the region of the interface. This significantly improves the stability of high modes as seen in Figure 6, where we compare 2D simulations of both Rev 2 and Rev 1 designs, with the roughness of the inner Be surface taken from a “line-out” through the measured 3D roughness so as to include several > 20 nm defects. This Rev 1 2D “line-out” simulation is also compared to the Rev 1 3D simulation in Figure 5.

3. Future Work
Although no degradation in neutron yield is seen in these simulations, 1D simulations with a simple mix model indicate that high mode mix does reduce capsule robustness. We plan to examine combinations of high mode mix and other errors, (e.g. low drive or mistimed shocks), to evaluate how
the overall margin is affected. We also plan to assess the importance of viscosity and mass diffusion, which will reduce growth at sufficiently high mode numbers, and may be important for our conditions.

**Figure 4.** Pseudo color plot of density at 14.6 ns from a 3D simulation of the Rev 1 target with measured roughness on inner and outer Be surfaces.

**Figure 5.** Mass fraction of Be vs. fractional fuel mass for 3D and 2D simulations, when the core temperature is 8 keV.

**Figure 6.** Mass fraction of Be vs. fractional fuel mass for Rev 2 and Rev 1 designs, when the core temperature is 8 keV. In Rev 2 the Cu concentration in the three inner doped layers is 0.5%, 1.0%, and 0.5%.

* This work was performed under the auspices of U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48.

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