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Preliminary Design Studies for a Hydro-Growth Radiography Platform to Study the Double Shell Ablator Joint

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Double shell target assembly requires mating two hemispheres of aluminum to form the ablator, and the design of the mating joint governs the dimensions of the gap that remains following ablator assembly. Radiographic data from double shell implosions with two different joint designs demonstrate the importance of having a smaller outer gap to minimize perturbation growth, but higher quality data is desirable for validating simulations of such localized engineering features. A double shell hydro-growth radiography platform is proposed to enable detailed measurements of the joint feature evolution for comparison to simulation predictions. The conservative design is based on a successfully fielded double shell keyhole target, but the tungsten inner shell is replaced with molybdenum to allow imaging with X-rays from a zirconium backlighter (16.3 keV). Eulerian radiation-hydrodynamics simulations with adaptive mesh refinement are used to predict joint feature evolution for several different joint designs. Synthetic radiographs produced from ablator-only calculations demonstrate that the evolution of different joint morphologies can be radiographed and distinguished. Feedthrough of the joint perturbation to a molybdenum inner shell is predicted to be measurable at a convergence ratio of 2.

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I. INTRODUCTION

The goal of inertial confinement fusion (ICF) is to compress deuterium-tritium fuel to sufficient densities and temperatures that thermonuclear burn can occur in the fuel.¹ Traditional approaches attempt to achieve this via direct laser irradiation of a spherical pellet of DT fuel (direct drive), as is done at the **OMEGA** laser facility,² or via indirect X-ray irradiation, where lasers are used to heat the walls of a gold hohlraum creating a bath of X-rays that are absorbed by the capsule (indirect drive), as is done at the National Ignition Facility (NIF).³ Hydrodynamic instabilities are believed to be a key contributing factor towards reducing the performance of current ICF implosions.⁴ Richtmyer-Meshkov (RM) instabilities^{5,6} grow as a result of vorticity seeded as a shock passes through a material interface with small-scale perturbations from surface roughness or engineering defects. Rayleigh-Taylor (RT) instabilities^{7,8} grow as a result of a mismatch between density and pressure gradients. RT modes are unstable when a lighter fluid pushes against a heavier fluid, and they are stable in the opposite case. RT occurs during the ablative acceleration phase as the low density, ablated plasma pushes against the unablated shell material. It also occurs during deceleration: as pressure builds in the low density hot spot, it slows down the incoming higher density shell that is working to compress the fuel. In convergent geometry, instability growth is enhanced due to Bell-Plesset (BP) effects.^{9,10}

Traditional ICF single-shell designs typically require large convergence, $CR \equiv r_0/r \sim 25$ – 35 , to compress the fuel to sufficient densities and temperatures for fusion reactions to occur. As a result, hydrodynamic instabilities are magnified greatly in these designs. Multiple shell concepts were proposed as a possible alternative to the traditional design,¹¹ as each shell would require less convergence than a single one. The double shell design¹² utilizes a high- Z inner shell and a low- Z ablator material, both of which experience less convergence ($CR \sim 3$ – 4 for the ablator and $CR \lesssim 10$ for the inner shell) during the implosion. The low- Z ablator is driven inwards, colliding with the inner shell and transferring momentum. The inner shell compresses the DT fuel, and the fuel assembly ignites and burns volumetrically, rather than relying on hot spot ignition and propagating burn into a cold fuel layer. The use of a high- Z inner shell is advantageous because it efficiently absorbs and re-radiates incident photons, trapping the radiation inside the fuel region and inhibiting radiative cooling of the fuel. A downside is that mix of the high- Z inner shell into the fuel impedes the fuel heating.¹³

The LANL double shell assembly calls for mating two hemispheres of aluminum to form the outer ablator.¹⁴ The design of the mating joint between them can significantly impact target assembly, specifically the dimensions of the gap that remains between them after the mating procedure. Los Alamos built and fielded several double shells with a 90° step-joint design at the NIF, and radiographic data taken during the implosion shows an equatorial band feature in the outer ablator resulting from growth of the joint perturbation during the drive phase. Pre-shot computed tomography (CT) scans of double shells assembled with the step-joint showed an outer gap that was roughly 10 μm wide and 53 μm deep, significantly larger than the design specifications. Cold welding of the aluminum hemispheres along the slip plane was believed to result in the inability to completely close the gap between the hemispheres. Subsequent designs utilized an angle-joint with a 45° slip plane, and CT scans indicated that the outer gap closed to the level of the CT resolution, ~ 5 μm and 13 μm deep. Radiographic data taken in-flight at the NIF shows a significantly smaller equatorial band resulting from the joint perturbation for these targets compared to the step joint.

Synthetic radiographs constructed from numerical simulations of these two joint designs show behavior that is qualitatively similar to the experimental data. The simulations are performed using LANL’s Eulerian radiation-hydrodynamics code, **xRAGE**,¹⁵ with adaptive mesh refinement (AMR). The AMR allows fine-scale features to be highly zoned, making it very well suited to modeling the isolated joint defect in a double shell. The equatorial band in the synthetic radiographs is considerably larger in the step-joint design than in the angle-joint design. However, quantitative comparisons are lacking at present. In an effort to validate **xRAGE**’s predictive capability for modeling these isolated defects, it is desirable to have higher quality measurements of the joint perturbation growth. To that end, a hydro-growth radiography (HGR)¹⁶ platform is proposed to provide higher quality radiographic data of the joint evolution. The standard HGR design requires inserting a gold cone through a portion of the capsule shell, and X-ray radiography is then used to image perturbation growth directly on one side of the capsule in a convergent geometry.

Here, we present preliminary design studies of an HGR double shell platform. The initial target design is presented in Sec. II, and 1D results showing expected transmission levels are used to constrain the choice of target materials. Results in 2D from outer shell only simulations are discussed in Sec. III, and simulations with a thin molybdenum inner shell and beryllium tamper are presented in Sec. IV. A discussion and conclusions follow in Sec. V.

FIG. 1. (a) Schematic of the VISAR double shell and the assembly process. (b) Inner shell placed on gold VISAR cone. (c) Lower ablator hemisphere placed on gold cone. (d) Foam cushion inserted around inner shell. (e-f) Upper ablator hemisphere being mated with lower. (g) Final target assembly. Images courtesy of T. Cardenas.

II. TARGET DESIGN

The initial design of the HGR double shell is based on the successfully built and fielded VISAR double shell. The VISAR target consisted of a $20\text{ }\mu\text{m}$ thick tungsten inner shell (slightly underdense $\sim 17\text{ g/cc}$) with a $390\text{ }\mu\text{m}$ inner radius, that was coated with a $30\text{ }\mu\text{m}$ thick beryllium (1.858 g/cc) tamper. The gold VISAR cone was inserted into the inner shell through a hole that was formed via electrical discharge machining. Although it was not needed for structural support (as a result of the VISAR gold cone), a machined CH foam was included between the inner shell assembly and the ablator, a $106\text{ }\mu\text{m}$ thick aluminum shell (2.7 g/cc) with an outer radius of $1110\text{ }\mu\text{m}$. In the VISAR design, the foam density was increased to 90 mg/cc from the point design's nominal 35 mg/cc to reduce the shock strength and inhibit blanking of the VISAR signal immediately after shock breakout. The ablator was fabricated from two hemispheres of aluminum, and the joint was located perpendicular to the VISAR line-of-sight to provide an unperturbed measurement of the implosion. A schematic of the VISAR double shell target and images from the assembly process are shown in Fig. 1.

The VISAR target demonstrated the feasibility of inserting a gold cone into a pre-fabricated

metal inner shell and placing an outer shell around the entire assembly. Preliminary designs for an HGR double shell take a conservative approach and call for a similar assembly using the same size inner shell. A major unknown for the HGR design is whether different metals can also be hole-punched in a similar fashion to the tungsten inner shell used in the VISAR target. Target fabrication efforts are needed to assess the viability of alternative materials, but we will proceed under the assumption that both chromium and molybdenum inner shells could be fashioned similarly.

In order to directly image the evolution of the joint perturbation, the joint must be placed along the HGR cone axis, as shown in Fig. 2, instead of perpendicular to it as in the VISAR design. There is a large amount of uncertainty as to whether the aluminum hemispheres can be mated around the gold cone in this way, however. Preliminary discussions with LANL's target fabrication group suggest that this should be feasible, but concerted research and development efforts are needed. A second concern is whether the joint formed in this way can be closed to within the design tolerances, and accurate metrology is needed for the as-built target to ascertain the size of the remaining gap. As an alternative, the target could be assembled as in the VISAR design, but with a trench machined into the outer shell directly opposite the cone axis, acting as a surrogate joint perturbation. It is not immediately clear if these two perturbations would be equivalent, though simulations indicate that the outer gap facing the radiation drive plays a much greater role in the joint perturbation evolution than the inner gap. For now, we proceed under the assumption that the HGR double shell target could be built with the joint in line with the cone axis and closed to within the design specifications.

We consider a 100 μm thick HGR cone with an inner diameter of 400 μm , which sets the size of the viewing window. The cone tip is nominally placed at the center of the inner shell, though deeper insertion (necessitating a larger hole in the inner shell) or shallower insertion (requiring a smaller hole in the inner shell) should also be acceptable from a design perspective. X-rays from the backlighter foil are directed through the HGR cone, propagating through one half of the target before passing through a pinhole array and gated framing camera system. For these design simulations, we consider the nominal NIF $6\times$ magnification system with the pinhole array located 90 mm from target chamber center (TCC) and the framing camera located 540 mm from TCC. Synthetic radiographs are produced by tracing X-rays from the cone tip through the target and onto the pinhole array. It is important

FIG. 2. Schematic of the HGR double shell design for (a) ablator-only configuration and (b) with inner shell assembly based on VISAR dimensions.

to note that we do not include contributions from inside the gold cone or gold blowoff in the hohlraum environment in this analysis. The interior of the gold cone is not expected to ablate significantly during the experiment, but a low density CH foam can be inserted if needed to inhibit the gold cone expansion into the line-of-sight. Including the gold blowoff in the hohlraum requires integrated capsule and hohlraum simulations, which are beyond the scope of this work.

The **xRAGE** simulations are driven with a frequency-dependent source (FDS) that is extracted from a **HYDRA**¹⁷ integrated capsule and hohlraum simulation of NIF shot N180321, a double shell which was driven with a 1.0 MJ laser pulse. Radiographic data indicates that this shot came in near round ($|P_2|/P_0 \lesssim 4\%$ and $|P_4|/P_0 \lesssim 4\%$), making it suitable for **xRAGE** capsule-only simulations with no imposed drive asymmetry. A flux multiplier on the FDS is included in the **xRAGE** simulations to match the predicted shell trajectories to the **HYDRA** results and experimental data.

FIG. 3. Illustration of the nominal joint (13 μm outer depth and 22 μm inner depth at 5 μm width) and the slip plane (dashed line) along which the hemispheres are in contact.

III. ABLATOR-ONLY SIMULATIONS

The simplest design for analyzing the evolution of the joint perturbation consists of only an outer shell with the inner shell assembly removed completely. Removing extraneous materials from the target enhances the contrast between the unperturbed and perturbed sections of the ablator, improving the quality of the measurement signal. As such, we initially consider ablator-only HGR designs before moving on to inner shell designs. We consider 4 different gap depths, which are modeled as helium gas at the hohlraum fill density of 0.3 mg/cc replacing a rectangular cross-section of the aluminum ablator. The nominal gap depth is 13 μm for the outer and 22 μm for the inner, shown in Fig. 3, while the other 3 have the slip plane displaced inwards or outwards from the outer surface: 23 μm outer and 12 μm inner, 8 μm outer and 27 μm inner, and 3 μm outer and 32 μm inner. All of these cases use a 5 μm gap width for the inner and outer gaps. In addition, for the nominal case (13 μm outer and 22 μm inner), we consider 2 μm wide gaps and 8 μm wide gaps.

The outer gap “area” (defined as gap width times gap depth) appears to be the dominant factor in controlling the perturbation growth, as can be seen in Fig. 4(a)-(f), which shows the evolution of the ablator-only targets for the six different joint morphologies being considered. The 13 μm deep outer gap that is 2 μm wide (area 26 μm^2) shows a similar perturbation as the 8 μm deep outer gap that is 5 μm wide (area 40 μm^2). Similarly, the 13 μm deep outer gap that is 8 μm wide (area 104 μm^2) appears similar to the 23 μm deep outer gap that is only 5 μm wide (area 115 μm^2). Larger gap areas are correlated with comparably larger perturbations of the ablator. The smallest outer gap depth of 3 μm shows only a modest

FIG. 4. Logarithm of density from ablator-only simulations with (a) Outer $3\ \mu\text{m}$, Inner $32\ \mu\text{m}$, Width $5\ \mu\text{m}$, (b) Outer $8\ \mu\text{m}$, Inner $27\ \mu\text{m}$, Width $5\ \mu\text{m}$, (c) Outer $13\ \mu\text{m}$, Inner $22\ \mu\text{m}$, Width $2\ \mu\text{m}$, (d) Outer $13\ \mu\text{m}$, Inner $22\ \mu\text{m}$, Width $5\ \mu\text{m}$, (e) Outer $13\ \mu\text{m}$, Inner $22\ \mu\text{m}$, Width $8\ \mu\text{m}$, and (f) Outer $23\ \mu\text{m}$, Inner $12\ \mu\text{m}$, Width $5\ \mu\text{m}$.

perturbation on the ablator at 6 ns, and the inner gap actually contributes more to this feature than in the other cases. Here, the ablator hole appears in the northern hemisphere ($z \geq 0$), while in the other cases the inner gap perturbation is washed out by the larger outer gap perturbation, and the ablator hole appears in the southern hemisphere ($z \leq 0$). In all cases, imaging with an HGR platform is expected to be possible at least until 7.5 ns when ablator material has converged to the HGR cone inner radius of $200\ \mu\text{m}$.

The gap width quantitatively increases with gap area, as can be seen in Fig. 5(a)-(f), which shows synthetic framed HGR images for the ablator-only simulations at 5 ns. Here, we have used a nickel backlighter (7.8 keV photons), since we only need to image through the aluminum ablator and not an inner shell. If a zirconium backlighter is used instead, there is too much transmission and the contrast drops appreciably. These images have been pinhole smeared ($15\ \mu\text{m}$ pinhole assumed) and motion blurred (Gaussian with a FWHM of 230 ps)

FIG. 5. Synthetic radiographs from ablator-only simulations at 5 ns with (a) Outer 3 μm , Inner 32 μm , Width 5 μm , (b) Outer 8 μm , Inner 27 μm , Width 5 μm , (c) Outer 13 μm , Inner 22 μm , Width 2 μm , (d) Outer 13 μm , Inner 22 μm , Width 5 μm , (e) Outer 13 μm , Inner 22 μm , Width 8 μm , and (f) Outer 23 μm , Inner 12 μm , Width 5 μm .

at a level that is comparable to the current double shell imaging shots. The dependence on gap area is clearly evident in these synthetic images. The 13 μm deep and 2 μm wide outer gap appears similar to the 8 μm deep and 5 μm wide outer gap, and the 13 μm deep and 8 μm wide outer gap appears similar to the 23 μm deep and 5 μm wide case.

FIG. 6. Vertical lineouts at $x = 0$ from synthetic radiographs of ablator-only simulations with (a) Outer 3 μm , Inner 32 μm , Width 5 μm , (b) Outer 8 μm , Inner 27 μm , Width 5 μm , (c) Outer 13 μm , Inner 22 μm , Width 2 μm , (d) Outer 13 μm , Inner 22 μm , Width 5 μm , (e) Outer 13 μm , Inner 22 μm , Width 8 μm , and (f) Outer 23 μm , Inner 12 μm , Width 5 μm .

Vertical lineouts of transmission from these synthetic radiographs illustrate the evolution of the gap feature in these targets, as can be seen in Fig. 6(a)-(f). These lineouts include the effects of pinhole smearing and motion blurring as discussed above. Transmission through the gap peaks at 5 ns between 30 and 40% depending on the joint morphology, and the apparent gap width peaks slightly later at 6 ns. Both the maximum transmission and the apparent width decrease after peaking as the ablator converges. The smallest outer gap (3 μm deep and 5 μm wide) shows the least variation in transmission, but it is still expected to be measurable.

IV. INNER SHELL SIMULATIONS

While the ablator-only target simulations suggest that the evolution of the joint perturbation itself will be measurable, the real impact of the joint feature is how it feeds through to the inner shell during the collision. Being able to directly measure this feedthrough is therefore of great interest for double shell designs. A series of 1D simulations was run to compare different inner shell materials and to provide a baseline for the expected hydrodynamic trajectories. Here, we considered inner shells made of chromium (Cr, nominal density 7.19 g/cc), molybdenum (Mo, nominal density 10.28 g/cc), and tungsten (W, nominal density 19.414 g/cc). The dimensions used in the 1D simulations are summarized in Table I.

TABLE I. Parameters of the HGR double shell targets.

Material	He ₄	Cr/Mo/W	Be	CH	Al
Outer Radius [μm]	390	410	440	1004	1110
Density [g/cc]	0.0003	7.19/10.28/19.414	1.858	0.035	2.7

Synthetic streaked radiographs are constructed from the 1D simulations, incorporating only half of the target as would be visible in an HGR platform. Here, we consider only a Zr backlighter with a photon energy of roughly 16.3 keV, as such foils have been successfully fielded, rather than any higher energy X-rays as might be possible with the ARC backlighter¹⁸ currently in development. Both the 20 μm thick Cr and Mo inner shells are transparent to Zr X-rays, with roughly 40–50% transmission through 20 μm , but the W inner shell is completely opaque, as can be seen in Figs. 7(a)-(c), respectively. As both Cr and Mo are predicted to have similar levels of transmission, we opted to use Mo in the subsequent 2D simulations, as its higher density pushes it closer to the nominal W inner shell.

The imprint of the joint perturbation on the inner shell is directly correlated to the outer gap area, as can be seen in Fig. 8(a)-(f), which shows the logarithm of density for 2D simulations of the six different joint morphologies with a molybdenum inner shell. The shells collide around 7 ns, and the joint perturbation begins imprinting onto the inner shell at that time. (There is relatively little structure visible in the inner shell prior to this.) HGR imaging is expected to be viable until just after 8 ns when the inner shell has converged

FIG. 7. Synthetic streaked radiographs looking through half of the shell constructed from 1D simulations with a 20 μm thick (a) Cr, (b) Mo, and (c) W inner shell. Selected lineouts show transmission curves at various times during the implosion.

beyond 200 μm (the radius of the HGR cone aperture). The joint perturbation gives rise to non-radial shocks in the foam cushion, resulting in a significant pressure asymmetry during the shell collision. The pressure asymmetry is largest just above and below the equator, and this causes some of the inner shell material to collapse on the equator. This is most evident in the larger outer gap calculations, but as we will see subsequently it is visible in synthetic radiographs even with the smallest outer gap area.

It is interesting to compare the calculations with the largest outer gap area: 13 μm deep and 8 μm wide to 23 μm deep and 5 μm wide. Recall that the ablator-only calculations of these two joint morphologies appeared qualitatively very similar. Here, however, the imprint

FIG. 8. Logarithm of density from inner shell simulations with (a) Outer 3 μm , Inner 32 μm , Width 5 μm , (b) Outer 8 μm , Inner 27 μm , Width 5 μm , (c) Outer 13 μm , Inner 22 μm , Width 2 μm , (d) Outer 13 μm , Inner 22 μm , Width 5 μm , (e) Outer 13 μm , Inner 22 μm , Width 8 μm , and (f) Outer 23 μm , Inner 12 μm , Width 5 μm .

on the inner shell differs substantially. The 13 μm deep, 8 μm wide outer gap shows holes being formed on the inner shell at about $\pm 5^\circ$ from the equator at 8 ns. In contrast, the 23 μm deep, 5 μm wide outer gap shows one set of holes on the inner shell at roughly $\pm 15^\circ$ from the equator with additional deficits of inner shell material observable at roughly $\pm 5^\circ$. In the latter case, the lateral distortion in the shock front has traveled slightly farther, and this results in a noticeable difference in the imprinting on the inner shell during the collision.

The late-time imprinting on the inner shell is evident in synthetic radiographs from these simulations at 8 ns, as shown in Fig. 9(a)-(f). Pinhole smearing and motion blurring have been included in these images as well. Calculations with smaller outer gap area show a dark band on the equator that arises from the molybdenum inner shell collapsing on axis as a result of the pressure asymmetry during shell collision. Regions of comparatively larger transmission are present above and below the equator, and they result from the lateral

FIG. 9. Synthetic radiographs from inner shell simulations at 8 ns with (a) Outer 3 μm , Inner 32 μm , Width 5 μm , (b) Outer 8 μm , Inner 27 μm , Width 5 μm , (c) Outer 13 μm , Inner 22 μm , Width 2 μm , (d) Outer 13 μm , Inner 22 μm , Width 5 μm , (e) Outer 13 μm , Inner 22 μm , Width 8 μm , and (f) Outer 23 μm , Inner 12 μm , Width 5 μm .

displacement of molybdenum. The vertical displacement of these “holes” in the inner shell depends on the size of the outer gap, with larger outer gaps resulting in larger apparent displacements. With the largest outer gap (23 μm deep and 5 μm wide), the additional structure of the inner shell appears as alternating light and dark bands in the synthetic

FIG. 10. Vertical lineouts at $x = 0$ from synthetic radiographs of inner shell simulations with (a) Outer $3 \mu\text{m}$, Inner $32 \mu\text{m}$, Width $5 \mu\text{m}$, (b) Outer $8 \mu\text{m}$, Inner $27 \mu\text{m}$, Width $5 \mu\text{m}$, (c) Outer $13 \mu\text{m}$, Inner $22 \mu\text{m}$, Width $2 \mu\text{m}$, (d) Outer $13 \mu\text{m}$, Inner $22 \mu\text{m}$, Width $5 \mu\text{m}$, (e) Outer $13 \mu\text{m}$, Inner $22 \mu\text{m}$, Width $8 \mu\text{m}$, and (f) Outer $23 \mu\text{m}$, Inner $12 \mu\text{m}$, Width $5 \mu\text{m}$.

radiograph.

The evolution of the perturbation imprinting on the inner shell becomes apparent when we consider vertical lineouts from the synthetic radiographs, as shown in Fig. 10(a)-(f). At early times, there is little variation in transmission, indicating that the molybdenum is responsible for most of the absorption and the aluminum outer shell provides comparatively little of the total absorption. Some structure is evident in the transmission at 6.5 ns before shell collision, reflecting the growing outer shell perturbation from the joint, but the variation in transmission here is minimal. The imprinting on the inner shell becomes visible at about

7.75 ns and this structure persists for a short duration afterwards before the inner shell converges beyond the inner radius of the HGR cone aperture. Cases (a)-(e) show high transmission regions just above and below the equator resulting from the displacement of molybdenum with a dark region at the equator, while case (f) shows multiple peaks in transmission from the more complicated structure that arises on the inner shell.

V. CONCLUSIONS

Preliminary design calculations for a double shell hydro-growth radiography platform to directly image the evolution of the ablator joint have been discussed. Six different joint morphologies were considered in this preliminary design study. All cases utilized a 40° angle joint with a diagonal slip plane that closes completely, but the displacement of the slip plane and the width of the outer and inner gaps were varied.

Ablator-only simulations indicate that the evolution of the joint perturbation should be experimentally measurable, and differences in joint morphology are expected to be discernible in the radiographs. Results from 1D simulations with an inner shell suggest that $20\text{ }\mu\text{m}$ of either molybdenum or chromium should be semi-transparent to zirconium X-rays, but molybdenum was used for the 2D design studies due to its higher density. The joint perturbation begins imprinting on the inner shell during the collision between 7 and 8 ns as a result of pressure asymmetries in the foam cushion. This displaces some of the molybdenum inner shell towards the equator, leaving a deficit of material above and below the equator. Dark and light bands are visible in synthetic radiographs at late times as a result of inner shell displacement.

In conclusion, the double shell hydro-growth radiography platform appears viable, assuming that the target fabrication challenges can be addressed. Future design work will extend this analysis to additional joint morphologies at higher laser energies that are more consistent with the point design target. Different inner shell materials will be considered along with higher energy backlighters that should be feasible with ARC.

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