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Author(s):	Schmitt, Mark J.
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Final Report: A Low Fuel Convergence Path to Inertial Confinement Fusion on the National Ignition Facility

Los Alamos LDRD Report-Directed Research

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Principal Investigator: Schmitt, Mark, J.
PI Email: mjs@lanl.gov

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ABSTRACT

After a decade of trying, the grand challenge problem of achieving hot spot ignition on NIF has not been achieved using indirect-drive of a high-convergence single shell capsule inside a hohlraum. Here, the alternate concept of obtaining volume-like ignition of liquid DT fuel via multi-shell implosion using laser polar direct drive (PDD) on NIF was assessed through theoretical analysis, computer simulation, fabrication development and implosion experiments on both the Laboratory for Laser Energetics' (LLE) Omega laser and the National Ignition Facility (NIF). This research has shown that multi-shell ignition has merit and should be further advanced by the National ICF Program to determine its ultimate limitations for achieving ignition on NIF.

At the onset of this project, it was not known if the predicted performance metrics on laser drive efficiency, collision kinetic efficiency, drive symmetry and target fabrication capability needed to achieve ignition level performance could be achieved. Through this work, many of these questions have been answered through simulation-aided design, fabrication development and experimental measurement. Moreover, during the course of this research, external collaborations with scientists from many institutions were initiated to leverage expertise further advancing the ramifications of these scientific efforts. Collaboration included:

- E. Mike Campbell and Riccardo Betti (LLE) on a joint paper investigating the characteristics of DT burn inside the inner gold shell of the Revolver triple shell ICF target.
- Steve Craxton and Pat McKenty (LLE) on 2D and 3D modeling of the direct drive of the Revolver ablator capsule which resulted in tweaks to the 3D pointing to obtain better drive uniformity for the NIF shots.
- Michael Rosenberg (LLE) set up of the FABS and SLTD scattered light diagnostics for our shots on NIF and post-shot analysis of the data for comparison with simulation.
- Haibo Huang (GA) and the GA target fabrication team to develop a new double-shell-on-cone target and first-of-their-kind low-density 3D-printed lattice materials
- Jason Mance (MSTS) to use time stretched photonic Doppler velocimetry (TSPDV) on Omega for the first time.
- Fred Marshall (LLE) to image an imploding shell for the first time using Fresnel zone plates (FZPs) that provided 2.5 um spatial resolution of the x-ray images[1].
- Phil Neilson (LLE) to detect the spectral emission from the center of an imploding mid-Z shell at convergence for the first time.
- Patrick Adrian (MIT) to provide experimental access for the development of a new x-ray-based penumbral imager to measure implosion hot spot electron temperature[2].

The research was divided into a progression of experiments, starting at Omega with sub-scale targets, and proceeded to NIF to demonstrate critical physics aspects of the laser-driven implosion efficiency and symmetry at nearly full scale. The design and execution of these experiments facilitated the parallel development of fabrication requirements and capabilities needed to construct multi-shell ignition targets. Although demonstration of many of the requirements for this concept were achieved, more work will be needed to finish demonstration of the symmetry requirements of this ignition concept.

TECHNICAL GOALS

The main goals for the proposed research were stated in the original proposal as:

(1) Develop the polar direct drive (PDD) ignition design including NIF laser requirements and target specifications

(2) Validate crucial Revolver multi-shell and direct-drive physics via experiments on Omega and NIF

(3) Demonstrate the unique Revolver target construction requirements through a parallel target fabrication effort

Achievement of these goals should result in a definitive conclusion on the viability of multi-shell ignition using PDD on the NIF.

These main goals were broken down into theory and simulation efforts to analyze in detail the drive and implosion physics of the target, experimental efforts to validate the design's physics-based requirements along with a parallel effort to fabricate state-of-the-art targets incorporating novel new materials. The design's physics assumptions to be validated included the following:

- The use of a large thin outer ablator shell should be used to reduce the laser intensity at the capsule surface which should eliminate pernicious laser-plasma instabilities that would otherwise reduce the laser drive to the capsule and cause asymmetry in the spherical implosion. Use of a light, thin shell should enable a high laser coupling efficiency of 9% to inward kinetic energy of the unablated fraction of the shell.
- The beam spots on NIF are limited to a maximum diameter of about 2 mm at the target (without costly and time consuming retrofitting with a new set of phase plates). Thus, the ignition design must also show that an efficient and symmetric implosion can be achieved using a beam-to-capsule ratio of about 1/3.
- Collision between the concentric shells transfers kinetic energy from the incoming to the outgoing shell with an efficiency that peaks when the shells have the same mass, depending on the specifics of the design. A significant amount of energy can be lost to heat and residual kinetic energy in the incoming shell. A predictive capability should be demonstrated to show the simulated fraction of energy transferred from the incoming shell to the outgoing shell is correct. A desired collision efficiency between the outer two shells in excess of 50% is needed for the ignition design.
- Implosion symmetry is very important if one is to obtain the needed compression to ignite the liquid DT fuel inside the third high-Z shell. Thus, it is important to show that the drive on the second shell has adequate symmetry for driving the third shell properly.
- High hydro-efficiency of the thin outer ablator shell requires a very low density of material inside the shell to facilitate its rapid and unimpeded acceleration during the laser drive, and to not result in excessive kinetic energy loss of the accelerated abator shell to the compression and heating of an excessive amount of inter-shell material prior to and during its collision with the second shell. Simulations indicate the ideal density for the inter-shell material should be in the 5 mg/cm^3 regime. No material with this density was

available at the onset of this project. The project needs to demonstrate that such low density materials can be fabricated and used in experiments to obtain the needed collision efficiency.

- Currently, the only facility for conducting ignition scale experiments is the NIF, which requires that direct drive targets be driven in a polar direct drive (PDD) laser configuration where the beams are not symmetrically arranged around the capsule. Designs for pointing the beams using the PDD configuration are needed to demonstrate the required implosion symmetry to achieve ignition.

SCIENTIFIC APPROACH AND RESULTS

Theory and Modeling:

Theoretical analysis and modeling was performed[3] to understand the implosion dynamics and volumetric-like burn evolution of Revolver's compressed fuel surrounded by a high-Z pusher as schematically shown in Figure 1. This included the following:

- The gold shell traps much of the radiation from the heated, keV temperature fuel, allowing the exponential run away of thermonuclear burn to begin at a lower ignition temperature of ~2.5keV.
- The fuel remains contained by the inertia of the surrounding high density (~2000 g/cm^3) compressed gold shell, facilitating the longer time needed to exponentiate to full burn.
- The fuel/shell interface is stable to Rayleigh-Taylor instability through the burn phase and for an additional 50 ps because of energy deposition at the gold shell wall that maintains higher pressure in the gold wall compared to the fuel it contains.

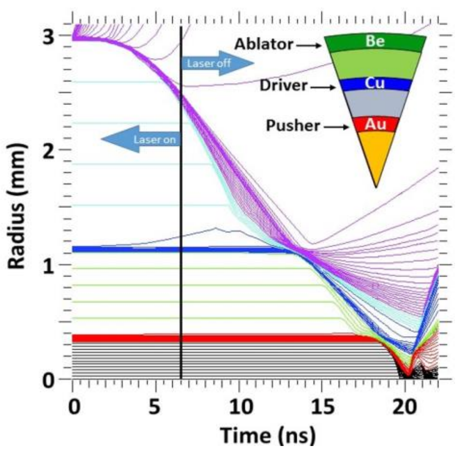


Figure 1. Revolver implosion diagram showing short laser drive region and target pie diagram inset with shell diameters of 6.0, 2.3 and 0.8 mm and thicknesses of 50, 50 and 60 μm, respectively.

- Decompression begins after the Marshak radiation shock wave propagates through the compressed gold shell and breaks out of its outer edge, terminating further burn.
- Atomic mix of gold from the inner shell into the DT fuel was modeled using the iFP code and shown not to be significant for the Revolver ignition design concept[4]

Modeling was performed to look at the laser requirements needed to drive a Revolver ignition target using NIF's 192 laser beams.

- It was shown analytically for symmetric direct drive (SDD) that reducing the beam-to-capsule ratio to 1/3 (available today on NIF) reduces the effective angle of incidence of the laser beams on the capsule by a factor of 2.5 compared to beams that match the size of the capsule, yielding higher laser absorption fraction and less refracted light that can seed laser energy loss and drive implosion asymmetry from cross-beam energy transport (CBET).

- It was shown theoretically for SDD that a laser with 192 beams (same beam number as NIF) can provide symmetric drive of the Revolver ignition design with a beam-to-capsule ratio of 1/3 if the beams are configured appropriately[5].
- Using a static hard-sphere model for the ignition target under SDD, the resultant analytic pointing parameters that produce uniform surface illumination was also shown to result in optimum symmetry and yield performance when used in dynamic 2D rad-hydro simulations.

Modeling was performed to optimize the laser drive in 2D for the revolver ignition design and for ablator shell and double shell collision target experiments for NIF.

- Modeling split quad pointing for 192 beam SDD using the HYDRA rad-hydro code determined that a drive uniformity of ≤0.5% peak-to-peak in the laser-driven ablator shell velocity from equator to pole is needed for target ignition.
- Optimization of the split quad pointing angles on NIF for PDD was performed using the HYDRA rad-hydro code by hand to achieve a velocity variation of 1.1% peak-to-peak in the velocity of the ablator shell from equator to pole. More work is required to reduce this variation of the required ≤0.5% for ignition.
- Higher spatial resolution simulations assuming SDD were employed to determine that cushion layers on the inner two shell can stabilize the target against high mode imprint and growth that would otherwise disrupt the compression of the fuel and prevent ignition.

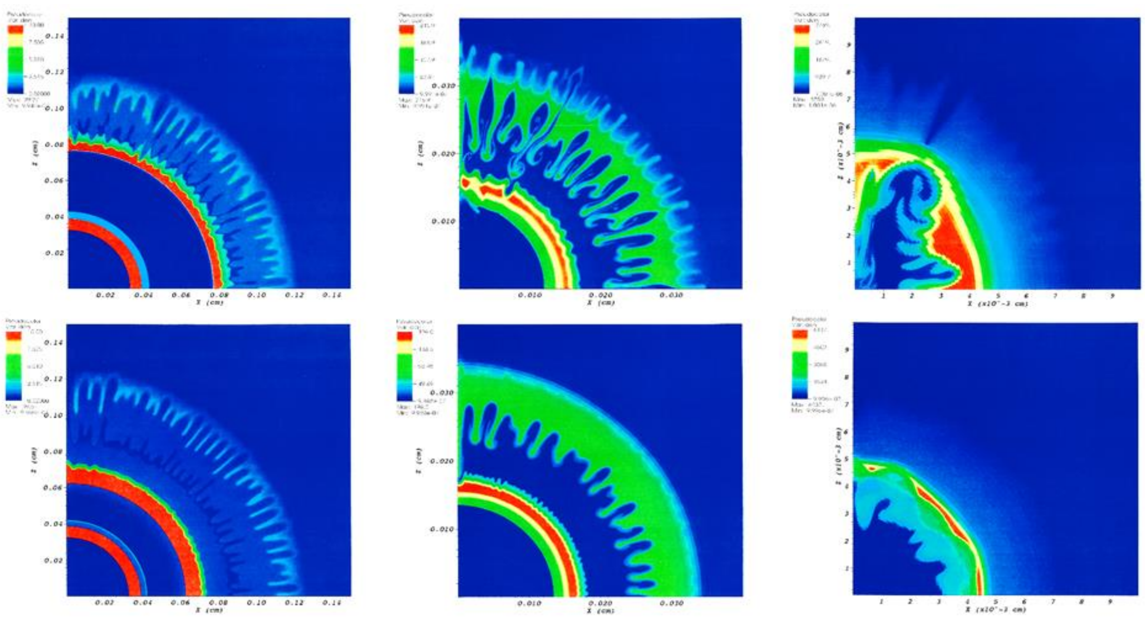


Figure 2. Density plots of the triple shell implosion of a Revolver target. The top row shows the dynamics of the outer (left), middle (center) and inner (right) shells with no cushion on the middle shell. The lower row shows the dynamics of the outer, middle and inner shells with a 50 μm Be cushion on the middle shell. Note that the DT fuel inside the inner shell has a large undisturbed region when the cushion is used (producing near 1D yield), while without it, the fuel region is penetrated by multiple jets (producing <1% of the 1D yield).

A comparison of the fuel compression without and with cushion layers is shown in Figure 2 where a simulation resolution of 0.25° was used.

- Offset of the target in the laser drive field and centroid offsets of the shells were simulated which indicated that the allowable tolerances were in the ~25um regime, within both current fabrication and experimental capabilities.

Experiments

2018 Omega

Revolver-18A/B on OMEGA studied ablator energetics, symmetry control, and laser-plasma instability mitigation in single-shell Be capsules, with varying capsule diameters (870, 1040, and 1220 µm) to achieve beam-to-capsule ratios spanning 0.3 - 0.4 with either 5-atm DD or no fill. The primary diagnostics were self-emission x-ray imaging to obtain detailed radius versus time trajectories of the ablator up to a shell convergence of three, and laser backscatter measurements using scatter calorimeters, and the full aperture backscatter diagnostic (FABS) to assess laser-plasma backscatter instabilities including cross beam energy transfer (CBET). Revolver-18A used symmetric 60-beam direct drive, and Revolver-18B used 40-beam polar direct drive, both with SG2 phase plates. As part of Revolver-18B, we obtained a few shots with backlighting to assess shell-dopant (Cu) and backlighter target (Zn, Fe) materials. Sufficient experimental data to validate our ability to model the Be-shell implosion trajectory and symmetry was obtained, and we verified the expectation of increasing absorbed laser energy with decreasing spot-to-capsule ratio, although the measured backscatter was systematically a few percent larger than calculated (for the NIF-

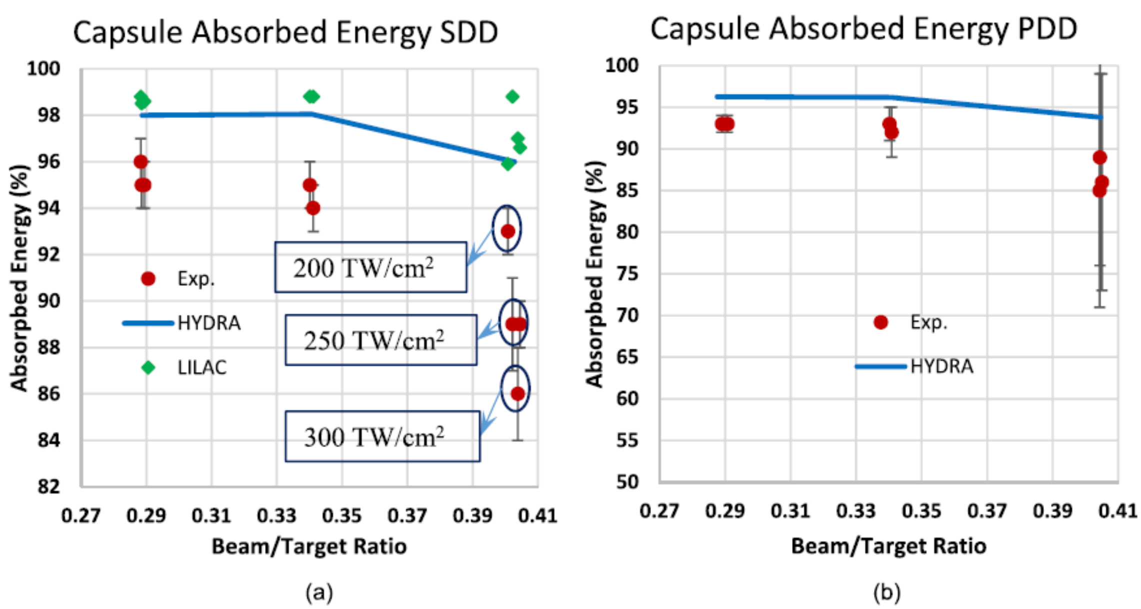


Figure 3. Absorbed capsule energy for different beam-to-capsule ratios for SDD and PDD drives. All red experimental data points in (a) are for a nominal laser drive of 250 TW/cm^2 unless noted otherwise. All data points in (b) are for a nominal laser drive of 250 TW/cm^2, except for the highest point at a beam-to-capsule ratio of 0.4 (shot 88410), which was taken at a laser drive of 199 TW/cm^2. The error bars correspond to uncertainty in the total absolute energy measured by the calorimeters combined with the variation in the measurements across all eight calorimeters. The results of 2D HYDRA simulations with no CBET are represented by the blue lines. The results of 1D LILAC simulations including a CBET model are also shown as green diamonds for the SDD case with LILAC absorbed energy values at a beam-to-capsule value of 0.4 corresponding to increasing laser drive intensities of 215, 260, 266, and 296 TW/cm^2.

relevant PDD case). The absorbed laser energy versus beam-to-capsule ratio is shown in Figure 3 indicating that the experiments did not result in significant CBET laser scatter for Revolver laser conditions of a beam-to-capsule ratio of 1/3. We also demonstrated the ability, using 12 OMEGA beams, to backlight the limb of Cu-doped Be shell using a Fe backlighter target.

Experiments on Omega during FY2018[6] demonstrated the following:

- Scaled Revolver ablator capsules demonstrated very high coupling efficiency (> 90% laser absorption by the capsule) at low laser intensity (~250TW/cm^2) for both symmetric and polar direct drive, obviating the pernicious effects of laser-plasma instabilities that have crippled more traditional ignition concepts for decades.
- The simulation codes seem to overestimate the absorbed laser fraction by a few percent which may be caused by differences in the modeled beam profiles or ambiguity in the polar angular scattered light profile assumed to calculate the total scattered light from the discrete experimental measurements.
- Laser drive efficiency using polar direct drive (the only direct drive configuration that exists today on NIF) is only slightly lower (~93%) that using the more ideal symmetric laser direct drive (95%) as shown in Figure 1 for these scaled Omega experiments. Thus, efficient capsule drive on NIF should be possible using NIF's current polar direct drive laser configuration.
- High capsule absorption efficiency is a strong function of the beam-to-capsule ratio and is close to optimum for a ratio of 1/3, the same value assumed for the Revolver design.

These positive results justified the initiation of parallel experiments on NIF starting in year two to validate the scaled high laser coupling fraction at full scale with 192 laser beams.

2019 Omega

The Revolver-19A/B campaigns evaluated the ablator-driver inter-shell collision relevant to the outer two shells of the Revolver triple shell direct-drive ignition design[7]. Using a novel new scaled direct drive two-shell-on-cone platform (Figure 4A), these experiments aimed to validate the post-collision inner shell velocity predictions from the radiation hydrodynamic code HYDRA using backlit images of the inner shell (Figure 4B). The measured inner shell velocity of 7.52± 0.59 cm/microsecond was in excellent agreement with the 7.19 cm/microsecond value predicted by HYDRA (Figure 4E), without the need for any adjustable parameters in the simulation[6]. These experiments provide confidence in the modeling capability currently being used for the Revolver triple shell ignition design, in particular, the ability to accurately model the shell collision process.

In addition to evaluating shell collisions, Revolver-19A/B developed a platform which is optimal for evaluating the feedthrough of Rayleigh-Taylor unstable growth, seeded by drive asymmetries and engineering features, to the inner shell. High-resolution (~2.5 micron) images of the outer interface of the inner shell were obtained in Revolver-19B (Figure 1C and 1D) through a collaboration between the LANL Revolver team and LLE. These images were the first obtained for a dynamic implosion using the newly commissioned Fresnel Zone Plate Imager. Preliminary analysis of the sharp edge between the high opacity inner shell and surrounding low opacity tamping layer suggest that Legendre modes up l=50 can be obtained from such images. Previously, such high mode studies would have only been possible using much larger capsules at the National Ignition Facility. These advances will allow the timely evaluation of mitigation schemes for high mode growth in multi-shell targets due to drive asymmetries and engineering features using subscale targets at the Omega Laser.

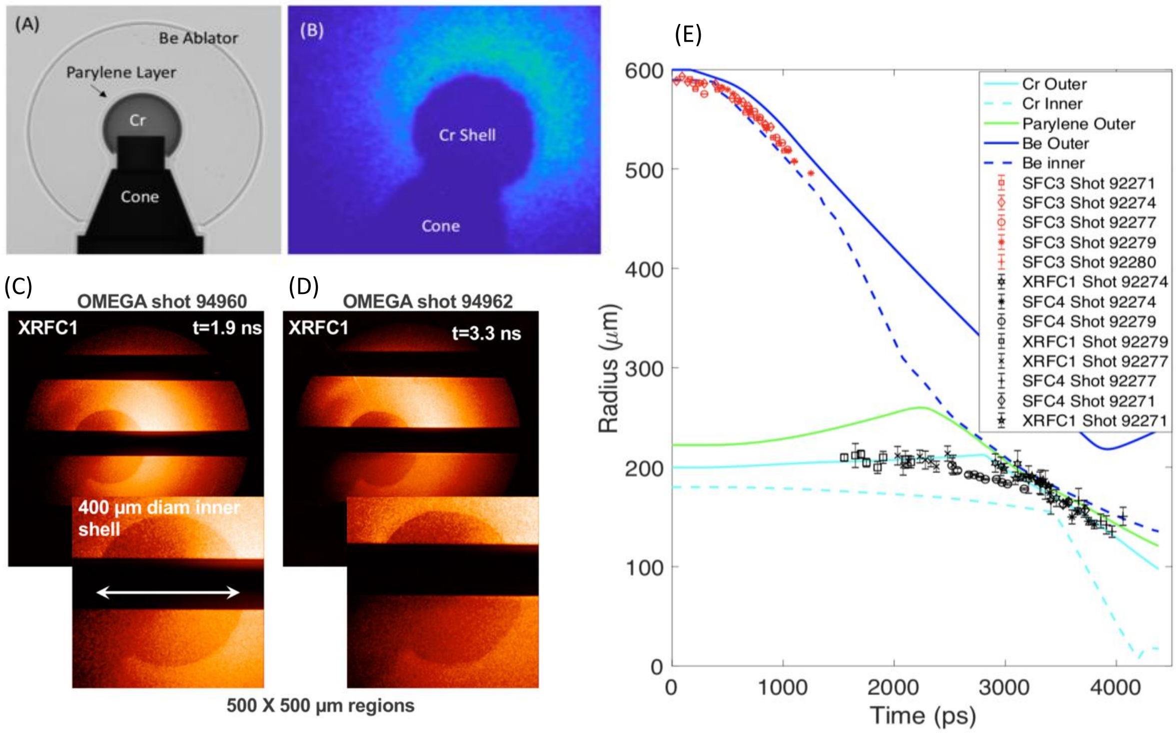


Figure 4. Summary of experimental and simulation data from Revolver 19A/B. (A) A pre-shot radiograph of the two-shell-on-cone target showing the target construction. (B) A backlit image of the inner shell after the collision with the outer shell corresponding to one of the black data points in figure 4E. (C) A ~2.5 micron resolution backlit Fresnel zone plate image of the inner shell from Revolver 19B at t=1.9 ns before the shell collision. (D) Similar to (C) but after the shell collision. (E) The measured outer radius from ablator self-emission images and inner shell backlit images compared with simulation predictions.

Experiments on Omega during FY19[8] demonstrated the following:

- A simplified two-shell-on-cone platform not requiring hemi-shell fabrication was invented, fabricated and used on Omega experiments.
- A low-Z cushion layer coating the inner shell acted as a filter to remove high spatial frequency modes on the outer shell from penetrating in to the inner shell.
- First experimental measurement of a low-Z outer shell driving a mid-Z metal inner shell.
- First use of a high opacity inner shell to facilitate 2.5 μm spatial resolution measurement of the inner shell's outer radius versus time.
- Inner shell shape analysis to Legendre mode *l*=50 using x-ray backlighting without Abel inversion for the first time.
- Record high collision efficiency measurement of 36% (inferred from the terminal outer velocity of the inner shell) obtained between two imploding ICF shells in agreement with code simulations.

2020 Omega

The Revolver 20 A/B/C campaigns evaluated the use of low average density (5 mg/cm^3 - 20 mg/cm^3) two-photon polymerization (2PP) printed structures as a support for the inner shell of a direct drive double shell target. The 2PP hemispherical structures, shown in the top row of Figure 5, were printed in a stochastic lattice geometry, and were composed of $CH_{1.72}N_{0.086}O_{0.37}$. From 1D and 2D simulations, it is expected that the lattices will disassemble by absorbing the penetrating x-ray radiation from the ablator's hot corona. The extent to which it can homogenize before bulk motion of the ablator depends on the lattice strut size, and potentially on the lattices ability to absorb x-ray radiation. In experiments, the extent of lattice disassembly is determined by measuring the perturbations imparted to the second shell, measured at a resolution of ~3µm using the Fresnel zone plate (FZP) imager. These experiments evaluated the performance of different lattice designs by varying the lattice strut size, average density, and by adding a high-Z Au coating to assist in the absorption of x-ray radiation. Each lattice design is shown in the first row of Figure 1. The corresponding FZP images are shown in the second row. The general trend observed is that lattices with thinner struts result in a more uniform inner shell for both ~5mg/cc and 20 mg/ cm^3 lattices. The uniformity does not only depend on the strut size. An effect of the lattice void size is also at play, this is indicated by the superior uniformity of the 20 mg/cc targets, regardless of strut size.

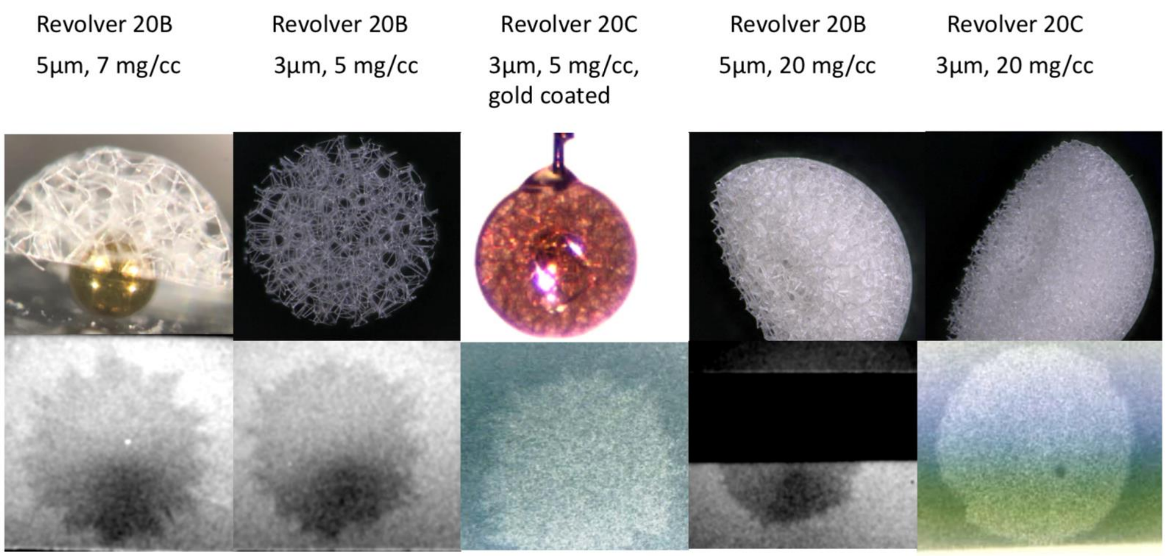


Figure 5. (Top) The five different 2PP lattice designs used during the Revolver 20B/C shot days had differing lattice strut sizes and mass averaged densities. The first image shows a 2PP hemi attached to the Cr inner shell of the direct drive double shell targets. The center image shows the gold coated lattice as viewed through the ablator of the assembled target. (Bottom) The corresponding FZP image for each target type. The black bar in the fourth image is due to clipping by the edge of the framing camera strip.

Experiments on Omega during FY20[9] demonstrated the following:

- Fresnel zone plates (FZPs) were used for the first time[1] on ICF implosions to generate x-ray images of the imprint and implosion dynamics of the inner shell of a double shell target at high spatial resolution (~3 um).
- First use of a 3D printed low-density lattice to suspend the inner shell inside the interlocking hemispheres that composed the outer shell.
- First experimental results showing the reduction on imprint as the inter-shell lattice structure is made finer.

On the down side, experiments to demonstrate the measurement of the velocity of the inside surface of the inner shell velocity using 3D printed fingers mounted inside the inner shell failed owing to a significant radiation flux inside the inner shell and loss of reflectivity from the finger tips. It was hoped that these measurements would bound the dispersion of the shell's radially-dependent implosion speed.

<u>Experiments on NIF</u>

Experiments also were conducted at the NIF facility starting in year two to obtain similar information but at near full ignition target scale and using NIF's 192 laser beams in a PDD configuration. Two single shell Be capsules were driven at low intensities followed by four double shell targets imploded using the ignition design laser intensity of 250 TW/cm^2 with the same temporal pulse shape as the ignition design. This allowed the assessment at full scale of ablative drive pressure and backscatter from laser-plasma instabilities for the proper ignition-scale coronal plasma scale lengths.

Experiments on NIF began with two single Be shell target shots (N190610-004 and N190827-001) driven at low laser drive intensity (130 TW/cm^2 and 165 TW/cm^2 at the target surface, respectively) to minimize any risk of laser damage resulting from these unique large 5mm diameter capsule direct drive experiments. This was the first time such large capsules were shot on NIF. The results showed that the capsule imploded slightly faster than the codes predicted and that the scattered light energy was low (with no risk of damage to the laser). Since the implosion dynamics were "better than predicted" in this low intensity regime and the symmetry of these PPD shots looked very good, the decision was made to proceed to full intensity experiments and validate the code predictions there.

Experiments with double shell targets (5 mm Ø x 80 μm CH ablator shell and 1.67 mm Ø x 65 μm Cr inner shell) were driven at the ignition design intensity of 250 TW/cm^2 showed that >98% of the laser was absorbed by the capsule. The CH hemi-shells were the first direct drive shots on NIF of a capsule with a joint. Self-emission images of the capsule during the drive show a controlled ablation of the joint, as shown in Figure 6(a). Experiments with this double shell configuration were performed with 4 different inter-shell materials to determine the effects of each on the ablator efficiency and collision metrics including collision kinetic energy efficiency and collision imprint. The implosion trajectories for the ablators are shown in Figure 6(b) and an image of the inner shells from each of these shots is shown in Figure 7. Their characteristic differences are:

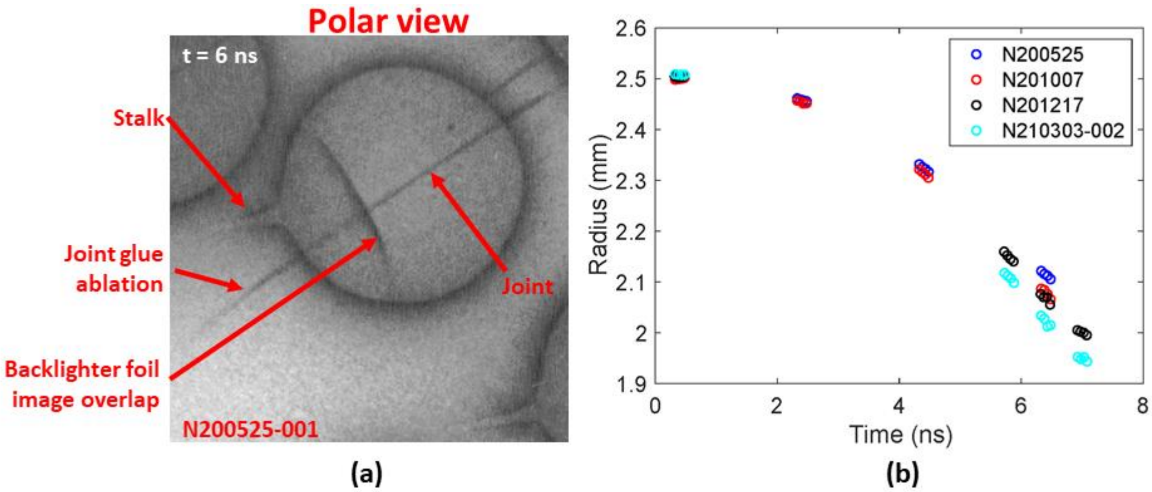


Figure 6. (a) Self-emission images of the outer capsule during the drive show a controlled ablation of the joint taken near the end of the laser drive pulse and (b) an analysis of the implosion trajectories of the outer shells of the 4 double shell shots showing improvement in speed with lower inter-shell material density and thinner ablator shell thickness.

1. A double shell target with a machined inter-shell foam material with 41 mg/cm^3 density imploded with fully defocused beams and 45 GHz smoothing by spectral dispersion (SSD) produced a slow inner shell implosion with good symmetry and no high frequency spatial modulations. (N200525)
2. A 3D printed 2PP lattice with 5 mg/cm^3 density stochastic Veronoi inter-shell lattice composed of coarse 20 μm diameter lattice struts (fabricated by MST-7) imploded with 5/6 smaller laser beam spots and 45 GHz SSD produced an inner shell implosion with large modulation imprint features. (N201007)
3. The same double shell with no material between the shells imploded using the smaller 5/6 laser beam spots and 45GHz SSD produced an inner shell implosion with large modulation imprint features, similar to shot 2. (N201217)
4. A 3D printed 2PP lattice with 11 mg/cc density cubic inter-shell lattice with finer 3 um diameter lattice struts (fabricated by GA) and a thinner 70um thick CH ablator shell

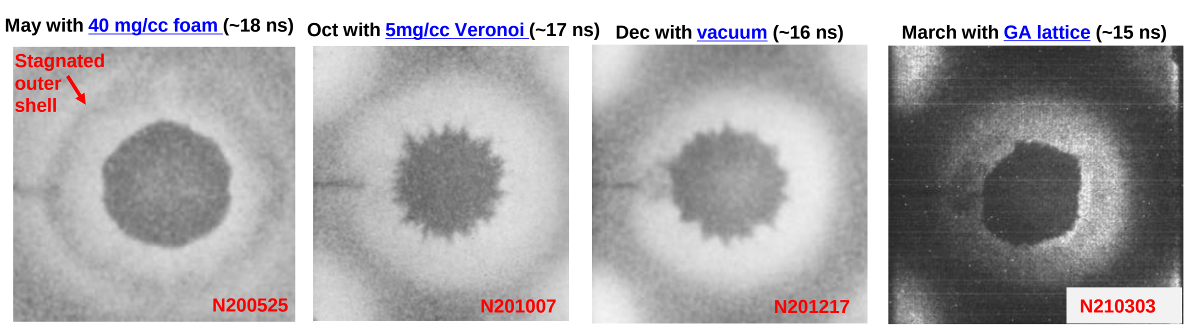


Figure 7. Backlit x-ray images of the imploding inner shells from the four Revolver double shell shots on NIF. Shot 1 shows good symmetry and evidence of the stagnated CH outer shell around the inner shell. Shots 2 and 3 show large imprint from the breakup of the outer shell. Shot 4 shows low mode asymmetry owing to clam-shelling of the two lattice inter-shell hemis. However, there is little or no high spatial frequency imprinting from the lattice and there is some evidence of the stagnated outer shell around the inner shell.

imploded with fully defocused beams and 90 GHz SSD produced an inner shell implosion with only minor high spatial frequency modulations, but with low mode asymmetries attributed to ill-fitting and clamshelled 2PP lattice hemis. (N210303-002)

All four shots used the same drive power and total drive energy of 1.1 MJ. Shots (1) and (4) used maximally defocused NIF beams with 35 mm defocus, while shots (2) and (3) were executed with beam defocusses that should have produced beam diameters that were 5/6 of those for the 35 mm defocus case. It was clear that the reduced defocus on shots (2) and (3) produced the enhanced imprint modulation of the inner shell. This was further confirmed by the absence of a residual outer shell appearing in the radiographs of the inner shell, indicating that the outer shell had broken up before its collision with the inner shell on shots (2) and (3).
Scattered light was also measure for the four double shell NIF experiments. Using the reduced defocus on shots (2) and (3) reduced the scattered light to less than 1%. The scattered light on shots (1) and (4) with the fully defocused beams produced 2 to 3 times more scattered light for and absolute scattered energy of about 2%. The somewhat higher scattered light is hypothesized to be caused by the larger laser beams producing more laser light near the limb of the capsule where it can refract and seed CBET gain and laser energy losses. However, for all shots, scattered power fractions in the 1% regime are extremely low and unprecedented for MJ-class ICF implosions, such that these measurements validate a major assumption for the Revolver ignition design of near-classical inverse-Bremsstrahlung laser absorption with effectively no adverse effects from laser plasma instabilities.

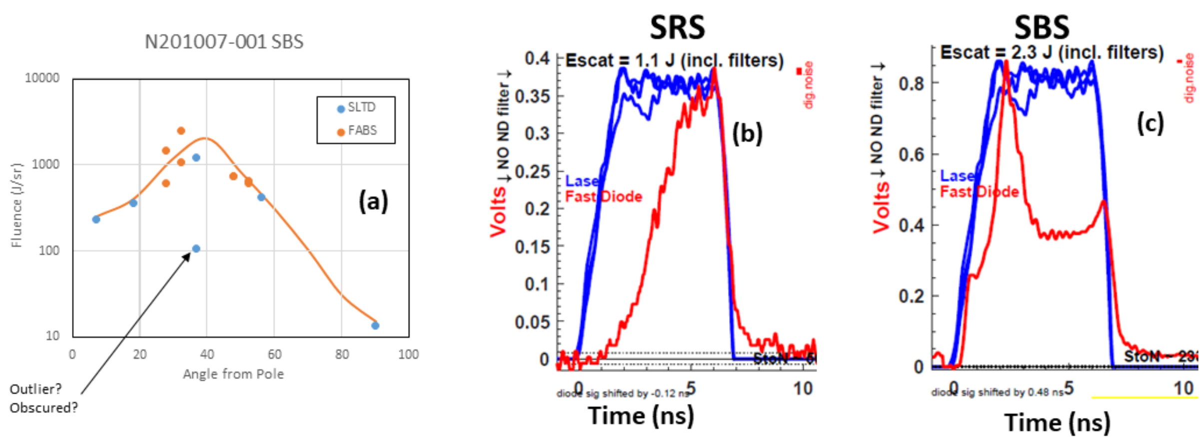


Figure 8. Examples of the scattered light for the Revolver NIF experiments including (a) plot of the time-integrated scattered light spatial distribution as a function of polar angle, (b) time-resolved SRS power (red) compared to the laser drive power (blue) and (c) characteristic SBS power versus time.

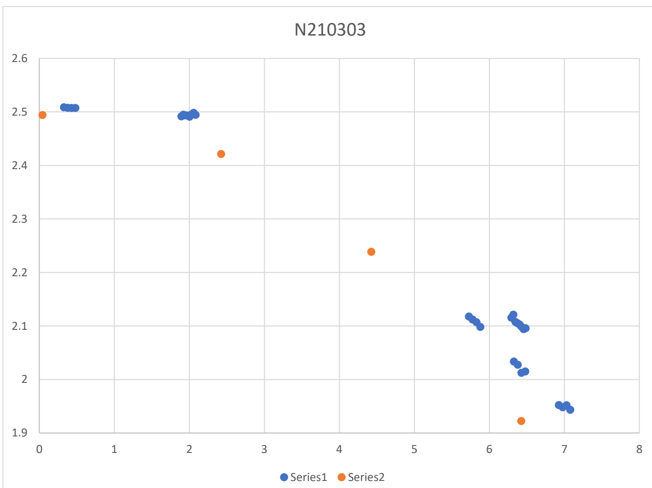
The angular dependence of the scattered light is shown in Figure 8(a) for shot N201007 (reduced defocus). The characteristic time dependence of the stimulated Raman scattering (SRS) and stimulated Brillouin scattering (SBS) signals are shown in Figure 8 (b) and (c), respectively. Note that the SBS power tends to rise throughout the laser drive, while the SBS power (red curve) peaks at the end of the laser drive ramp (blue curve), relaxes and then rises again toward the end of the laser pulse.

In summary, the major accomplishments from the NIF shot campaign were:

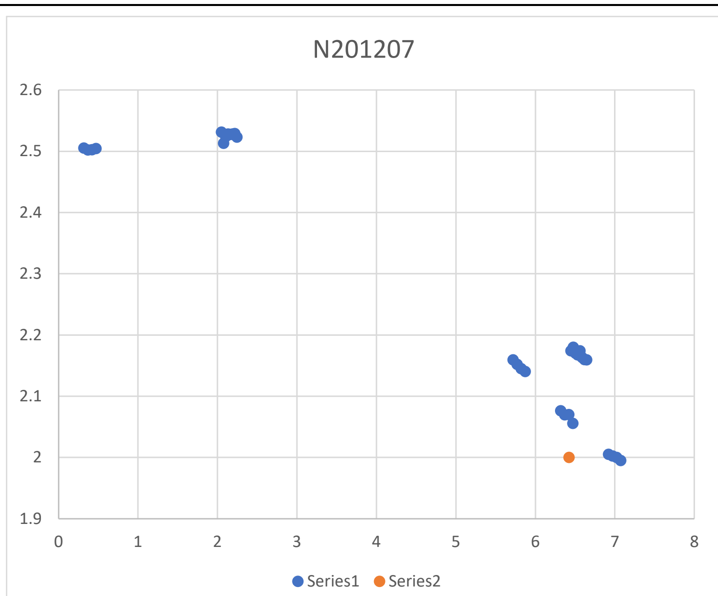
- First direct drive implosion of a double shell on NIF

- First characterization using self-emission x-ray images of a directly driven shell joint on NIF.
- Demonstration of ~99% laser absorption by the laser Revolver capsule sans any significant backscatter laser plasma instabilities
- Fabrication of 5 mg/cm^3 average density lattice materials for the first time.
- Use and characterization of lattice materials in double shell targets
- Collection of double shell data for evaluating both hydro-efficiency and collision efficiency data on NIF for different inter-shell materials with average densities in the range of 5 – 41 mg/cm^3.

We close this section with plots comparing the implosion trajectory of the outer shell R vs t data (blue) with Hydra simulations BK33a (red) for N210303-002 and BK24 for N201207.



R vs t comparison for March shot. BK33a simulation values.



R vs t for the December vacuum shot. BK24. Need to check if sim is peak value.

MISSION AGILITY

As stated in our original proposal, we expected the National ICF Program to fund a follow-on Revolver direct drive project to continue to advance the development of this novel ignition concept. Through discussion we have had over the past year, LANL's ICF Program Office and Program Manager, John Kline, recognizes the significant advances we have made developing this new concept. Our expectation of follow-on funding has been realized to a limited extent as $400k of ICF funding has been provided in FY21 (so far) to continue efforts at a low level. Moreover, the ICF Program has encouraged us to continue our shot campaign on NIF, providing 2 shots in FY21 and an additional shot in the first half of FY22. We will continue to work with them to ramp up funding for this effort in FY22 with the expectation of more NIF shots in the second half of the year.

As already mentioned, our target fabrication efforts has resulted in the capability to manufacture novel 3D low density materials that are imperative for the Revolver ignition concept and important to future science campaign efforts such as Marble and Campaign 10's Double Shell Project.

TECHNICAL VITALITY

As documented above, the project has contributed significantly to the advancement of novel new capabilities for the National ICF Program and for LANL experimental science. The development of additive manufacturing using two-photon polymerization (2PP) 3D printing was a major accomplishment for this DR. It drove competitive development efforts at LANL and GA that are now transforming the fabrication of complex targets with novel new low density designer lattice materials needed for multi-shell ICF designs and HED heterogeneous mix experiments being performed for code validation. The field is now on the cusp of performing additional ignition relevant experiments that require fabrication techniques and materials with properties that were unavailable at the onset of this project (including direct drive wetted-lattice ignition research).

Diagnostic capabilities for ICF experiments were also advanced on several fronts by this project. Our collaboration with MSTS on TSPDV enabled the first use of this diagnostic at an ICF laser facility and promises to advance the capability to simultaneous measurements of both shock and particle speeds in planar and spherical geometries in a strong shock regime. A 2022 LDRD-ER has been submitted to advance this concept. Our collaboration with LLE on Fresnel zone plate (FZP) imaging resulted in the first ever images of an imploding capsule using this diagnostic that provided several-fold increase in the spatial resolution of capsule symmetry. Our FZP data was used to model asymmetry modes up to mode 50, unprecedented for ICF, but needed to understand how asymmetry is affecting the quest for symmetric igniting implosions. LANL's ICF Program is also looking at adapting the FZP imaging diagnostic we used on Omega for future high spatial resolution imaging on NIF for their Double Shell experimental campaign.

Our initiative and successful demonstration of imploding large capsules, directly driven at low surface intensities, has now spread beyond our project's efforts. Our group continues to be involved with the multi-Laboratory National Nuclear Survivability Testing Program (NNSTP) efforts at NIF (led by Brent Blue, LLNL) whose targets recently have been migrating toward a capsule very similar to the large Revolver ablator shell. LANL's RadChem experimental efforts on NIF are also migrating to large directly driven capsules in collaboration with the NNSTP. On a separate front, LLE is now collaborating with us to adapt our two-shell-on-cone target platform (from our FY19 Revolver Omega experiments) to perform strong shock (~100 Mbar) EOS experiments at the Omega laser facility.

WORKFORCE DEVELOPMENT

This project was responsible for the post-doc recruitment and retention of Brett Scheiner as a new staff member in XCP-6. Moreover, because of his involvement with our experiments on Omega, Brett was able to become the first ever trained Omega experimental PI in XCP-6. The project also supported a young staff member, Brett Keenan in XCP-6, and provided him the opportunity to learn how to run a rad-hydro code for the first time, design NIF experiments and configure a backlighting diagnostic set up for these shots. Cross-training staff with both modeling and experimental skills is crucial for developing the best research scientists at LANL. In addition, project funding provided to the target fabrication group, MST-7, resulted in the hiring of Lynn Goodwin to spearhead the 2PP printing efforts that are now being used by other projects at the Laboratory. The advancement of 3D printing for ICF and HED targets in MST-7 drove a competing development effort at General Atomics (funded using their internal R&D funding) that has now produced a burgeoning 3D fabrication capability for future ICF and HED experiments across the complex in addition to our home-grown 3D fabrication capability in MST-7. On the experimental side, thanks to funding through this DR, a young staff member in P-1, Carl Wilde, was able to become a responsible investigator (RI), i.e. a formally trained and recognized experimental lead on NIF, significantly broadening his professional capabilities and increasing the number of trained LANL staff that can conduct experiments on NIF.

CONCLUSION

Research results accomplished under this LDRD-DR project have had positive ramifications for the Revolver ignition concept and for laser driven ICF and HED science. Pioneered by this LDRD-DR, several programs are now adopting large directly-drive capsules as an efficient way to couple the maximum laser energy into their targets. The double shell platform from our Omega experiments is now finding new application as a diagnosable platform for strong shock EOS measurements. In the future, more effort will be required to understand more fully the EOS of heterogeneous "lattice" materials and the ultimate tradeoff between reducing lattice density and producing a lattice with sufficient mechanical strength properties needed for target assembly. Moreover, a viable PDD pointing design that obtains < 0.5 peak-to-peak velocity variation across the capsule surface still needs to be demonstrated, preferably using 3D simulations. With adequate effort, we are confident this can be done, especially if the constraints on the laser spot size (determine by NIF phase plates and their current defocusing capability) can be relaxed. It is hoped this work will continue into FY22 under the LANL ICF Program.

ACRONYMS AND DEFINITIONS

CBET – Cross beam energy transfer laser-plasma scattering instability
FABS – Full aperture backscatter diagnostic
FZP – Fresnel zone plates
GA – General Atomics, San Diego, CA
HED – High Energy Density
HYDRA – LLNL's 3D ICF rad-hydro code
ICF – Inertial Confinement Fusion
LANL – Los Alamos National Laboratory
LILAC – LLE's 1D direct drive rad-hydro code
LLE – Laboratory for Laser Energetics at the University of Rochester, Rochester, NY
LLNL – Lawrence Livermore National Laboratory
MIT – Massachusetts Institute of Technology
MSTS – Mission Support and Test Services, LLC, Santa Barbara, CA
NIF – National Ignition Facility
NNSTP – National Nuclear Survivability Testing Program
OMEGA – LLE's 60 beam laser facility in Rochester, NY
PDD – Polar direct drive
SBS – Stimulated Brillouin scattering laser-plasma instability
SDD – Symmetric direct drive
SRS – Stimulated Raman scattering laser-plasma instability
SLTD – Scattered light time-history detector
TSPDV – Time stretched photonic Doppler velocimetry diagnostic

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