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Panel 3 Report: Implosion Hydrodynamics

V. Gocharov, O. A. Hurricane

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Panel 3 Report: Implosion Hydrodynamics

Panel Leads: V. Gocharov[1] & O.A. Hurricane[2]

Panel Members: S. Abarzhi[3], D. Arnett[4], T. Clark[5], J. Glimm[6], A. Randewich[7], P. Gauthier[8], J. Fincke[5], M. Key[2], J. Knauer[1], S. Haan[2], D. Hicks[2], K. Mikaelian[2], A. Miles[2], M. Masakatsu[9], C. Nakhleh[10], H. Robey[2]

Additional Input from: C. Barnes[4], D. Clark[2], J. Edwards[2], J. Lindl[2]

[1]University of Rochester, Laboratory for Laser Energetics (LLE)
[2]Lawrence Livermore National Laboratory (LLNL)
[3]University of Chicago
[4]University of Arizona
[5]Los Alamos National Laboratory (LANL)
[6]State University of New York, Stony Brook
[7]Atomic Weapons Establishment (AWE)
[8]Commissariat l'energy Atomique (CEA)
[9]University of Osaka
[10]Sandia National Laboratory (SNL)

Introduction

Using an ablation pressure of ~100 Mbars over a period of ~10 ns, the implosion hydrodynamics of an ICF capsule have always been a balance between obtaining high implosion velocities (> 370 km/s), necessary to create sufficient fuel densification ($\rho R > 1\ g/cm^2$) and stagnation pressure (> 400 Gbars), while simultaneously attempting to avoid hydrodynamic instabilities and avoid raising the DT fuel entropy much -- either of which frustrates fuel densification and hot spot creation. Ideally, an ICF implosion should have yield within about 50% of 1D, but present evidence from NIC suggests that is not the case and it is presently difficult to estimate the degree to which irradiation asymmetries or high-mode mix, respectively, are contributing to this behavior. If the NIC implosion can resolve any low-mode implosion hydrodynamics issues, there remains the significant challenge of achieving the needed convergence ratios in excess of 30+ without generating unacceptable mid to high-mode instability growth. Indeed, in the handful of NIC shots where the implosion speed was pushed up above ~300 km/s, and which had less than 8% ablator mass remaining, hot spot ion temperature and yield both dropped significantly, with an increase in x-ray brightness, which is consistent with excessive perturbation growth due to hydrodynamic instabilities.

Status of the Physics

Presently, design simulations can only approximately predict the ablation pressure history during the laser pulse even in a 1D average sense. Since code inadequacies were known before the NIC campaign began, several experimental platforms were developed to normalize the implosion as necessary. Data needed to normalize the implosion come from convergent ablator (ConA) trajectory experiments that measure ablator radius, $R(t)$, implosion velocity, $V_{imp}(t)$, and thickness as well as experiments that measure velocity of a leading shock up to the time of coalescence of fourth shock launched during the rise of the main drive to peak power. It appears that the ablation pressure of the implosion is currently over predicted by ~ 1.5X during the 2nd pulse, the 4th rise acts as if delayed and reduced, with the peak radiation drive being over-predicted by ~ 15% in flux. This could be due to some combination of hohlraum physics affecting the x-ray drive incident on the capsule, and/or the efficiency of the ablator of converting x-ray energy into ablation pressure through ionization. In addition to influencing the apparent efficiency of the implosion, the detailed temporal history of the ablation pressure or ablator response can affect the fuel adiabat (ρR), and mix.

A performance cliff attributed to mix, has been observed at an implosion velocity of ~ 300 km/s in several NIC implosions. Simulations in 2D have not been able to assess correctly the observed mix. Experimentally, the observed mix could be due to a combination of factors including, less efficient rocket (more mass ablated at given velocity, hence more feed-through), more ablation front growth possibly due to unfavorable 1D pulse shaping, 3d effects that are not included in current 2D simulations, and enhanced growth in thin spots due to low mode asymmetry. Theoretically, it's possible that the simulation predictions of instability growth are too optimistic possibly due to (but not limited to) overestimating the smoothing effects of ablation-front stabilization or insufficiently representing the structure on and in the ablator and ice (coming from manufacture or from physics such as species separation effects).

Evidence from nuclear spectra from multiple lines of sight suggests significant ρR asymmetry in the assembled cold fuel (with the ρR at the pole of the capsule measured to be ~2x that of the waist). This can reduce the efficiency with which implosion kinetic energy is converted to stagnation pressure resulting in lower stagnation pressures, densities, and yields. For the inferred in-flight fuel adiabat ~ 1.5±0.1 the inferred hot spot density is ~ 2x too low, and the fuel ρR is low by ~ 20%. A number of factors could contribute to this including (but not limited to), mix, low mode asymmetry (hot-spot volume) and associated vortex flows ($p_{3D} \sim p_{1D} - \frac{1}{2}\rho v_{non-radial}^2$), kinetic effects as well as a significant "5th shock".

Opportunities for Progress

Uncertainties in laser propagation and x-ray conversion physics (Panel 1) and x-ray transport and ablation physics (Panel 2) compound uncertainties in implosion hydrodynamics (topic of this Panel) primarily through uncertainty in the drive pressure history as a function of solid angle and time, $P(\theta,\phi,t)$, and preheating of the capsule. With a drive that is calibrated to mimic the capsule trajectory and shock timing observables, it is found that 2D simulations, with measured surface and ice roughness, still over-predict stagnation pressure (but not T_{ion}) by ~2x and yield by ~4x (with alpha-particle deposition turned off) to ~10x (alpha-particle deposition turned on). By construction, these 2D simulations match the measured down-scatter ratio (*DSR* ~ ρR).

If drive related asymmetries can be resolved and the desired time dependent ablation pressure is be recovered, the problems of the implosion hydrodynamics reduce to managing instability, mix, while delivering the required hot-spot formation (via ablation of the inner ~10% of the DT ice and set by thermal conductivity in implosion kinetic energy) and hot-spot stagnation pressure which is most strongly affected by implosion speed ($p_{stag} \sim p_{abl}^{1/3} v_{imp}^3/\alpha$).

Priority Research Direction 1: Investigation and Control of Ablation Front Instability

It's likely that ablation front instability is presently under-predicted in simulations for a variety of reasons. Current code simulations indicate that many of the targets now being shot have more simulated ablation front growth than that was expected for the NIC point design. More than expected ablation front growth results primarily from higher ablator opacity, which has been increased as a consequence of the higher than expected x-ray preheat. Also, there are strong indications from NIC data that ablative instability is more aggressive than originally expected. Due to the way the ignition capsule hot-spot is formed, ablator material only needs to penetrate into the last 10% of the DT ice to show up in the hot-spot. The NIC near term tactic is to thicken the ablator and turn the laser drive power up, but this may not help.

The panel recommends the following research directions on this topic:

- *Face-on radiography Richtmyer-Meshkov (RM) and Rayleigh-Taylor (RT) experiments with a perturbed ablator and the full NIC drive pulse to compare against simulation predictions.* While many high energy density physics experiments have been performed previously for one or two shock RM instability at an interface, four shock (e.g. NIC-like pulse) studies of RM instability have not been performed. Testing the veracity of simulation predictions of the ablator after the passage of the fourth shock is key for correctly calculating the RT instability growth that subsequently follows. Validating simulation unstable growth predictions under multiple shocking is particularly prudent for the NIC capsule point design that presently has many interfaces within the ablator (the dopant layers). Since ICF target design trade-offs of doping levels, doping profile, shell thickness are made based upon simulation predictions of unstable growth it is clearly desirable for the predictions to be as correct as possible.
- *Design and shoot a series of implosions with varying picket to trough ratios in order to possibly find an implosion less sensitive to ablative Rayleigh-Taylor instability and improved compression.* Unvalidated simulations of ICF capsule instability growth presently indicate that the ablation front instability growth factor at peak implosion velocity as a function of mode number can be significantly modified through control of the strength of the 1st picket in the drive pulse with negligible affects on adiabat. Similarly, simulations of ICF implosions with different drive troughs immediately after the 1st picket show a reduction in growth factor vs. mode number at peak velocity (see figures below). These results suggest the existence of a potential knob which improve the instability performance of ICF capsules.

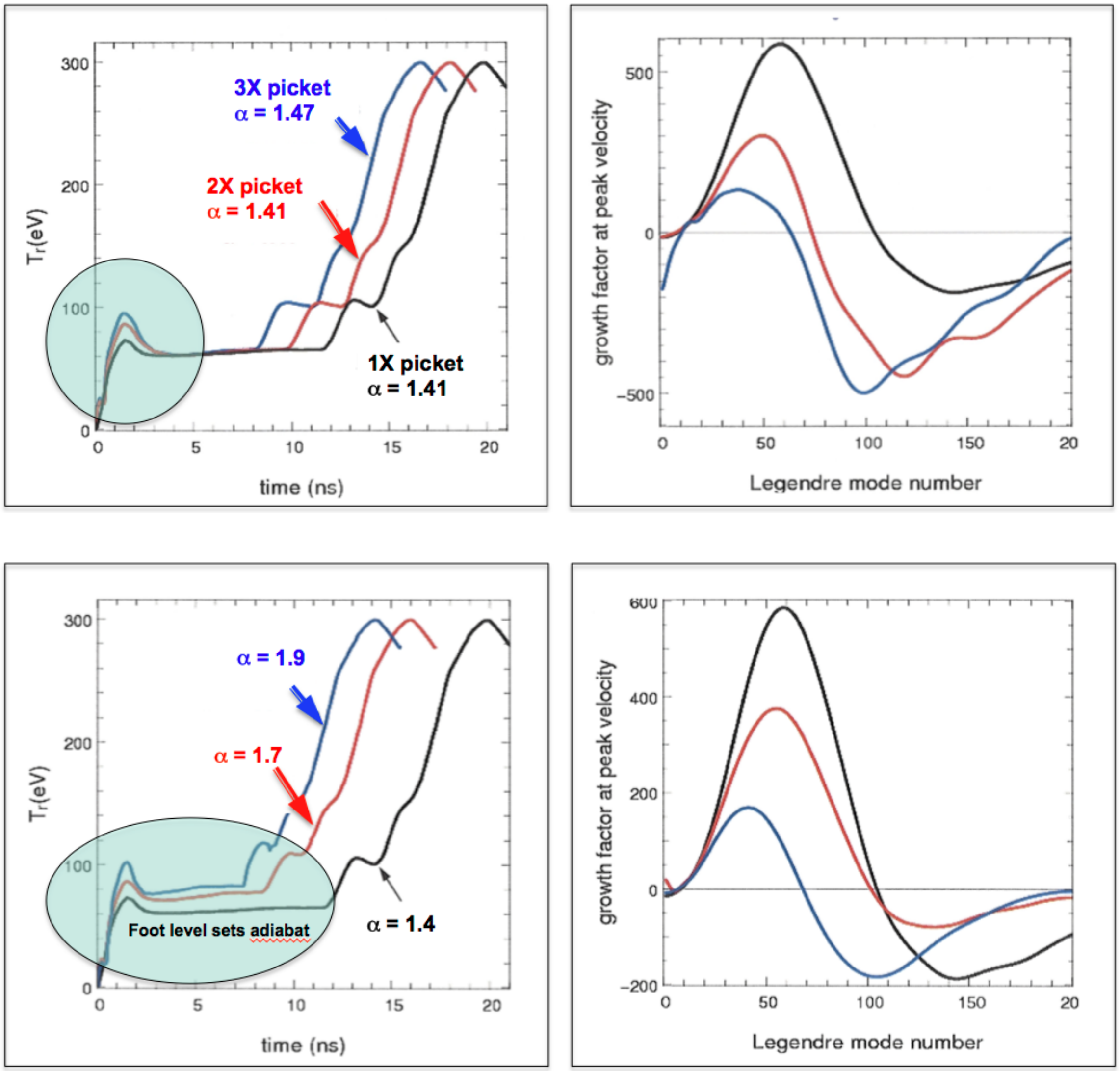

Figure: Altering the 1st picket in the drive (upper left) potentially shifts the extrema of the ablation from instability growth (upper right) without much impact on fuel adiabat. Increasing and shorting the foot level of the "trough" of the drive pulse (lower left) potentially reduces the instability growth for many mode numbers (lower right). Figures courtesy of the NIC target design team.

- *Thicken the DT ice layer (~ 20 um) or thicken the ablator and ice together in order to move the hot-spot forming inner ice region away from the ablator and delaying the time at which the central shock reflection re-enters the ablator.* Due to the density difference between the DT ice and the ablator, thickening the ice has much less impact on implosion speed that does thickening the ablator. Altering the ice thickness requires no capsule fabrication changes and is a simple test of the depth of penetration of fingers of ablated material.

- *Perform planar ablator experiments with graded CH and alternate ablator materials and diagnose the ablation profile side-on and use VISAR on the face of the ablator to diagnose v(t).* Some of the unexpected ablation front instability growth in the NIC point design could be due to poor understanding of the material properties (e.g. equation of state, kinetic effects, etc.) under ICF conditions. Testing alternate ablator materials (in a planar geometry for simplicity and efficiency of target fabrication) would illuminate whether other choices of ablator materials behave in a more predictable fashion.
- *Test implosions with alternate ablator materials.* Presently, beryllium and high density carbon (HDC) ICF targets are "on-the-shelf" and while not necessarily optimized ignition designs, testing them could quickly illuminate questions about hohlraum-ablator coupling and instability growth. In particular, is the observed behavior more-or-less what is expected from simulations? Some target fabrication research and development is required to field other alternate ablator capsules.
- *Use scaled implosions (w/ less energy) to perform a more comprehensive study.* Data is at a premium here and since laser glass damage effects are cumulative, more shots can be performed if targets can be designed to use less energy per shot.

Priority Research Direction 2: Mix in Extreme High-Acceleration Implosions Driven by Multiple Strong Shocks

Experience with simulations of implosions with large Atwood numbers and low remaining mass, is that the simulations can produce results that *look* like "turbulence." For well-designed implosions, simulations do not look turbulent even in 3-D with mode numbers up to ~1000, about where ablative stabilization sets the minimum scale length. When simulations are adjusted to recover the measured 1D implosion hydrodynamics, the results do not look turbulent, but these same simulations still over-predict the measured yields. While turbulence and mix are often associated, diffusion processes and successive folding flows, for example, can produce "mix" in the absence of turbulence. Furthermore, recent theoretical analysis show that the statistical properties of accelerated mix should depart substantially from canonical turbulence. In particular, when compared to canonical turbulence, accelerated mix has a higher level of correlation, smaller fluctuation contributions, stronger dependence on initial conditions, and steeper spectra.

NIC data show indications of mix at smaller implosion speed than was anticipated by pre-NIC simulations. Clearly, the simulations are missing something. So far it is unknown if the observed mix is "independent" from initial conditions. Obviously capsules with different surface-finish but the same 1D implosion parameters would be the way to determine if mix is independent of initial conditions. On the calculation side, if 2D simulations with an enhanced thermal conduction (to mimic gas/ice atomic mix) successfully explain the data at hand (yield & T_{ion}), then it is a strong argument for introducing a sub-grid scale model in the code. In fact, 2D simulations performed with DT thermal conduction multipliers show that a conductivity multiplier of 2.0 gets the T_{ion} about right but is still far from getting the right yield (D. Clark, *Private Communication* 2012). A thermal conductivity multiplier of ~ 10x appears necessary to explain the observed yield degradation, but this would drive the T_{ion} too low. It is possible that excess numerical ablation at the ice/gas interface is a cause of underestimation of hot-spot mix.

The panel recommends the following research directions on this topic:

- *Perform implosions with increased adiabat of the main fuel to reduce the sensitivity of target performance on mix and obtain a scaling relationship for measured yield/simulated yield (Y.O.C. – "yield over clean").* Presently, the NIC point design has focused upon keeping the fuel adiabat as low as possible to obtain the maximum amount of convergence. Stiffer fuel implosions would converge less and likely suffer less from mix. Mapping out the scaling of Y.O.C. with adiabat may provide data useful for mapping out the cliffs associated with mix for the purpose of avoiding such cliffs in subsequent target design iterations.
- *Test implosions with roughened ablators/ice and observe the sensitivity to initial conditions*. A systematic study where key target interfaces are roughened would quickly help isolate from where the material responsible for the observed mix cliff originates helping to target amelioration efforts.
- *Design and perform implosion experiments with separated reactants (e.g. CD ablator + pure T fill) with a measurement of reaction history if possible.* If diagnostically measureable, a separated reactant experiment could quantify the amount of ablator material that mixes into the hot-spot of the implosion as a function of capsule and drive shape design.
- Develop a large eddy simulation (LES) representation with a parameter free sub-grid model elaborating the analytical and numerical modeling needed to couple microscopic and macroscopic scales for instabilities and mix induced by strong shocks and strong accelerations.

Priority Research Direction 3: Hot-spot Formation and Fuel-Shape Physics

The final phase of the capsule implosion hydrodynamics culminates in the ablation of the innermost part of the DT fuel that creates the hot-spot. The optimization that leads to successful hot-spot formation is a balance between having enough implosion velocity and a tolerable amount of mix (~10's of ng). As the imploding shell of fuel decelerates, distortions in the hot-spot/main fuel boundary shape grow. Reduced thermal conduction and mass ablation from the shell of fuel into the hot-spot could lead to enhanced Rayleigh-Taylor growth during deceleration and smaller stagnation pressures.

Obtaining more data on the hot-spot and cold-fuel condition are key to resolving issues with NIC capsule performance and model-data inconsistences.

The panel recommends the following research directions on this topic:

- *Design and, if justified, test implosions using a small pore size doped wetted foam to enhance imaging of the hot-spot and possibly improve the imaging of the cold fuel. Use spectroscopy to obtain direct measurement, through the dopant, of the hot-spot density.* Presently, hot-spot shape in the NIC implosion is only roughly inferred from emission measurements while the cold fuel shape is not directly known. For the purpose of performing the required low-mode symmetry tuning and for code validation obtaining accurate imaging of the hot-spot and cold fuel shape are highly desirable.
- *Perform high-mode "direct" 3D simulation, with known initial conditions, of a practical number of NIC shots and also inter-compare results from various codes using a simplified, but representative, 3D high-mode implosion test problem.* Since the observed stagnation pressures is only a factor of 2 above simulation it is in the realm of possibility that fully 3D simulations with fully represented initial conditions may, without the need for additional physics, capture the observed degradation of pressure and yield. In particular, a 3D simulation that has no symmetry boundary or axis may have enough non-radial motion (at mesoscopic scales) at stagnation time to explain the stagnation pressure problem.
- *Improve the physical database conductivity tables and address more quantitatively the effects of magnetic field on electron conduction.* Inaccurately representing electron conductivity can obviously impact the simulations ability to calculate the transfer of heat in an implosion and impact the formation of the hot-spot plasma which originates from the inside layer of the DT ice.

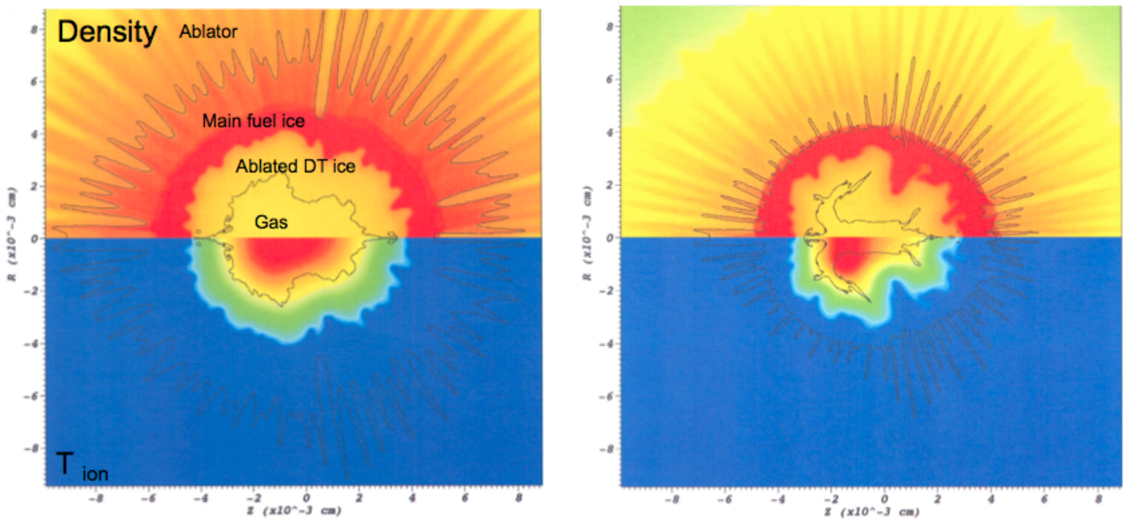

Figure: A 2D mode 100 ARES simulation of an ICF implosion with realistic surface roughness, shows the expected late-time implosion morphology and hot-spot. Prior to self-heating from alpha-particle deposition, mechanical pdV work produces heating that spreads radially outward into the DT fuel via electron conduction (assuming conduction and radiation losses don't dominate). This ablated fuel forms the hot-spot and is many times the mass of the DT gas that occupies the volume at the center of the capsule.

Conclusions

In order to demonstrate gradually increasing performance of ICF targets on NIF, each stage will require improvements in many aspects of the implosion hydrodynamics that can be carried into the next stage of hot-spot formation and stagnation. The exact steps that will be needed to achieve each goal will depend upon what is found from the experiments and studies outlined above. The elements described above, this panel believes, hold the highest leverage on improving the implosion hydrodynamics of ICF targets on NIF. These improvements may be direct or indirect through improved understanding of critical physics such that target design improvements can be made.

Sidebar 1 – The Difference between 2D and 3D Calculations and Physics

Simulation of inertial confinement fusion implosions need integrated modeling using complex multi-physics codes. The physics operates over scales from the hohlraum size to the hot-spot radius. With present capability of computing, to achieve useful time-to-solution of the modeling, assumptions are generally made that the physics can be approximated with azimuthal (along the hohlraum axis) symmetry in two-dimensions (2D).

However, the physics of hydrodynamic motion are very different in 2D and 3D. An example is shown from astrophysics where there are significant differences in flow morphology and velocity amplitude in simulations of stellar burning, although the size of the mixed region was similar in both 2D and 3D. An active area of future research will be to appropriately link more realistic 3D hydrodynamic simulations to the integrated modeling and better calculate effects of instability and mix.

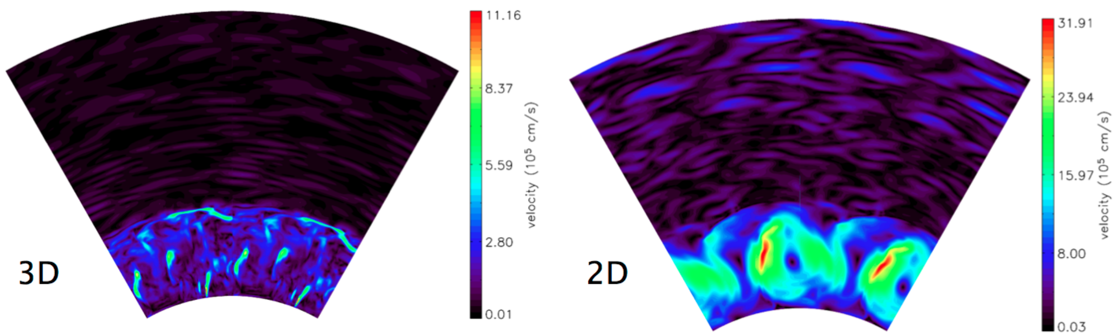

Figure from C.A. Meakin and D. Arnett, *Ap. J.*, **667** (2007) 448.