Three-dimensional HYDRA simulations of National Ignition Facility targets


Lawrence Livermore National Laboratory, Livermore, California 94551

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The performance of a targets designed for the National Ignition Facility (NIF) are simulated in three dimensions using the HYDRA multiphysics radiation hydrodynamics code. [M. Marinak et al., Phys. Plasmas 5, 1125 (1998)] In simulations of a cylindrical NIF hohlraum that include an imploding capsule, all relevant hohlraum features and the detailed laser illumination pattern, the motion of the wall material inside the hohlraum shows a high degree of axisymmetry. Laser light is able to propagate through the entrance hole for the required duration of the pulse. Gross hohlraum energetics mirror the results from an axisymmetric simulation. A NIF capsule simulation resolved the full spectrum of the most dangerous modes that grow from surface roughness. Hydrodynamic instabilities evolve into the weakly nonlinear regime. There is no evidence of anomalous low mode growth driven by nonlinear mode coupling. © 2001 American Institute of Physics.

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I. INTRODUCTION

The National Ignition Facility, under construction, is a 192-beam frequency tripled (λ = 0.35 μm) Nd:glass laser system designed to generate shaped pulses delivering 1.8 MJ at a peak power of 500 TW. Detailed computer simulations have been performed for a variety of indirectly driven targets designed to achieve ignition on NIF.1–8 These designs employ a cylindrical hohlraum which converts laser light to x rays, resulting in a more symmetric drive on the capsule. The hohlraum designs have been modeled extensively with the two-dimensional (2-D) multiphysics radiation hydrodynamics code LASNEX.9 The large number of beams on NIF are intended to produce a nearly axisymmetric radiation flux onto the capsule. There exist, however, a number of issues one would like to examine with direct 3-D simulations. These include the possibility that the discrete laser spots cause significant azimuthal asymmetries in the wall motion. Such an asymmetry might affect implosion symmetry hydrodynamically or by generating asymmetries in the radiation flux. The ability to propagate light through the laser entrance hole in the absence of an axisymmetric illumination pattern should also be assessed. A direct 3-D hohlraum simulation allows us to calculate the radiation flux on the capsule taking into full account such effects as wall motion, laser spot broadening, albedo variations, and volumetric emission from the hohlraum channel.

In addition to the asymmetry caused by the radiation drive, perturbations on the capsule surfaces seed hydrodynamic instabilities, which can cause shell breakup and quench capsule ignition. For a broad range of modes the growth factors due to hydrodynamic instabilities are sufficiently large that perturbations progress into the nonlinear regime, where saturation effects and mode coupling are important. The higher nonlinear saturation amplitudes obtained in three dimensions are well established.10–16 Besides assessing a capsule’s ability to withstand these larger amplitudes, we wish to examine the effects of nonlinear mode coupling in the presence of the full spectrum of modes. We are interested in whether nonlinear mode coupling between high order modes generates low mode asymmetries which could threaten ignition.

This article presents examples of how HYDRA is being used to simulate in three dimensions these aspects of the targets designed for the NIF. The remainder of this article is organized as follows. In Sec. II we describe HYDRA. A description of the hohlraum simulation results is presented in Sec. III. We discuss in Sec. IV results from a highly resolved, large solid angle simulation of hydrodynamic instabilities on a NIF ignition capsule.

II. HYDRA

HYDRA is a 2-D and 3-D multiphysics radiation hydrodynamics code. It now has the essential physics required for simulations of NIF targets. HYDRA is based upon arbitrary Lagrange Eulerian (ALE) hydrodynamics, employing modern monotonic artificial viscosities to stabilize shocks. A variety of algorithms are available for controlling grid motion, including weighted equipotential relaxation. Second order monotonic advection is performed on scalar fields and momentum. Material interfaces are resolved using interface reconstruction.17

HYDRA includes a laser raytrace and deposition package that calculates ray orbits with second order accuracy and includes ponderomotive effects. A heavy ion deposition package is available. Radiation transport is handled either with Monte Carlo photonics or with flux limited multigroup diffusion. A variety of LTE (local thermodynamic equilibrium) and non-LTE (NLTE) opacity models are available, including inline XSN,18 and the newly developed linear re-
spontaneous equation of state

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An online server allows LTE opacity tables to be generated for arbitrary mixtures. Electron and ion conduction are treated using flux-limited finite element diffusion operators. Conductivities and electron-ion coupling coefficients are obtained from the model of Lee and More.

Modeling of thermonuclear burn includes multigroup charged particle transport and isotope production and deple-
tion. Neutron energy deposition can be treated adequately in the free streaming limit for inertial confinement fusion (ICF) capsules, which are thin to neutrons. A variety of methods are available for solving matrices which arise from the operator splitting employed. For large matrices two scaleable multigrid methods are available from the HPRE solver library. Many equations of state are available, including the inline quotient equation of state (QEOS), the EOS IV tabular data base, Sesame tables and the LEOS library.

HYDRA has been modified to run on distributed clustered SMP architectures, using a strategy based upon POSIX threads, OpenMP, and the message passing interface (MPI) library. High parallel performance has been demonstrated on problems using up to 1680 processors of the ASCI SKY machine at Lawrence Livermore National Laboratory. HYDRA has been used in the design and simulation of a range of laser-driven experiments.

III. HOHLRAUM SIMULATIONS

We first consider a scale 0.6 hohlraum which was designed for the 96-beam configuration initially planned for NIF. A schematic of the target is shown in Fig. 1. The hohlraum measures 6.0 mm long by 3.3 mm in diameter. A gas fill mixture of equal amounts of He–H at $6 \times 10^{-4}$ g/cm$^3$ is intended to control the motion of the hohlraum wall material. A 0.8 $\mu$m thick polyimid window on each laser entrance hole maintains the gas fill. The hohlraum wall is fabricated from a mixture of equal amounts of U–Pb–Ta–Dy–Nb. This “cocktail” mixture is designed to yield higher energy conversion efficiency than pure gold hohlraums. A plastic liner covers the high-Z wall material at the laser entrance hole. The capsule has a polyimid ablator ($C_{25}H_{10}N_2O_3$) 95 $\mu$m thick enclosing a cryogenic layer of deuterium and tritium (DT) 48 $\mu$m thick. The center of the capsule contains DT gas at a density of 0.3 mg/cm$^3$.

We simulated $\frac{1}{2}$ of the hohlraum with two symmetry planes, one at the equator and one running through the hohlraum axis. The simulation models all of the hohlraum features described above. For the purposes of this simulation the hohlraum was illuminated using the 192-beam pattern of full NIF. Light comes into the laser entrance hole in two cones. The inner cone is composed of beams aimed at 23.5 and 30 degrees to the hohlraum axis, and the other has beams at 44.5 and 50 degrees. The 48 beams which enter the quarter hohlraum are aimed at 12 locations and are represented by 12 beams in the calculation. Eight of these groups are associated with the outer cone. Each beam group is represented in the laser package by 300 rays, with an elliptical focal spot. The relative power in the cones is dynamically varied during the 10.0 ns pulse to minimize the time-varying pole-to-waist asymmetry, which is described as a $P_2$ Legendre polynomial.

Power losses from the beams due to laser power instabilities were not modeled. For conditions calculated in the laser entrance hole at time of peak laser intensity the back-scattered power is predicted to be less than 10%. Beam steering, due to ponderomotive forces, is not resolved since it arises from individual speckles in the laser, not modeled here. For conditions at the time of peak illumination intensity, when the beam deflection is largest, the predicted deflection is only 0.5 degrees. Magnetic fields, which are not modeled, can affect the electron temperature profile in the low density regions inside the hohlraum, but are not expected to have a significant effect on the drive and the capsule implosion symmetry. Two-dimensional LASNEX hohlraum simulations that include magnetic fields support this conclusion. For a broad base of hohlraum experiments on Nova there is good agreement with 2-D LASNEX simulations which also neglect the effects mentioned above. This good agreement indicates those effects have a minor impact on hohlraum performance when the experimental parameters are properly chosen.

At the time of this writing the Monte Carlo photonics package did not yet function with the material interface tracker. This simulation was performed using multigroup radiation diffusion, inline XSN NLTE opacities, and the quotidian equation of state. The deposition of laser energy should be represented quite accurately with the model employed here. The laser beams are the significant source of 3-D asymmetries in the hohlraum wall and channel. Energy losses from the laser hot spots, due to conduction and radiation emission, are expected to be calculated with reasonable accuracy using this model. The response of the target is adequately resolved with the mesh employed. The mesh has several zone widths in each direction across the laser spots. When the mesh resolution was increased by a factor of 2 to 3 in the directions tangent to the wall, little change resulted in the calculated density profiles. A fine initial mesh spacing of 38 Å in the direction normal to the wall was employed at the inner hohlraum surface. A comparison between 2-D simulations having initial zone thicknesses of 5 and 38 Å at the inner wall showed no significant differences in the bang time or in any of the density or temperature profiles.

Figures 2(a)–2(c) shows the electron temperature contours on a cut-away view of a mesh surface. For the three
times shown this surface remains near the laser spots. The laser beams burn through the polyimid window and then into the gas for 900 ps before the outer ring begins heating the wall appreciably. Initially individual laser spots are visible. These laser spot quickly broaden, converting the contours at the outer cone into a true ring pattern. The beams forming the inner ring reach the wall at 2.2 ns. Due to the smaller number of beams in the inner ring and the approximation of reflection symmetry about the equator the laser hot spots in the inner ring remain more distinct than for the outer ring. By the last time shown, the electron temperature has evolved to a very high degree of azimuthal symmetry, as expected.

The density profile in the interior of the hohlraum shows the gas effectively controls the wall motion. Only slight deviations from axisymmetry occur in the density profile in the main hohlraum volume. These variations are largest in the vicinity of the laser entrance hole. The energetics from this hohlraum have been compared with a 2-D axisymmetric simulation. The radiation temperatures obtained from these simulations are nearly identical.

The radiation diffusion approximation results in an artificially symmetric flux of radiation onto the capsule. Accordingly the capsule maintains a very high degree of spherical symmetry, after converging by more than a factor of 30. This indicates that the hohlraum generates no significant 3-D hydrodynamic asymmetry that affects the capsule. This particular target design is not intended to ignite the capsule, which produces a yield of 3 kJ.

The radiation flux onto the capsule can be obtained from the 3-D hohlraum simulations. The transport equations are integrated directly on rays which foliate $2\pi$ solid angle at locations on the capsule surface. This method takes into account the convergence of the capsule during the implosion.

Three-dimensional components of asymmetry can also...

FIG. 2. (Color) Electron temperature on a cut-away view of mesh surfaces at (a) 1.0 ns, (b) 1.75 ns, and (c) 5.75 ns. This surface is initially in the hohlraum interior 100–300 $\mu$m closer to the hohlraum axis than the wall gas interface.

FIG. 3. (Color) Motion of hohlraum materials shown on simulation boundaries at (a) 1.0 ns, (b) 7.0 ns, and (c) 11.2 ns. Hohlraum wall is cyan, plastic liner is dark blue, He–H gas fill is purple, polyimid window and ablator are green and DT is red.
be calculated using a viewfactor code. Those calculations allow for the time variation in the wall albedo and the capsule convergence. But the viewfactor analysis lacks potentially important effects such as volumetric emission and laser spot broadening due to thermal conduction.

We have calculated the intrinsic radiation flux from the quarter hohlraum simulation. We note that the approximations to the illumination pattern introduced by the symmetry planes are quite significant. The symmetry plane at the equator modifies the illumination pattern to intensify the inner cone laser spots on the equator. We have compared coefficients obtained with the two approaches outlined for the spherical harmonic modes that have significant amplitudes. For the effective illumination geometry of this simulation these modes are $Y_{44}$, $Y_{64}$, $Y_{84}$ and $Y_{88}$. In spite of the physical effects omitted by the viewfactor code analysis, the two methods produce a similar picture of the 3-D intrinsic radiation asymmetries in this problem. These techniques give us the capability to calculate radiation flux inside the hohlraum from a direct 3-D simulation. We can impose this radiation flux on the capsule and assess its effect on implosion symmetry. In the future we will employ these techniques in full hohlraum simulations using the exact NIF illumination geometry.

IV. MODELING OF HYDRODYNAMIC INSTABILITIES

We study hydrodynamic instability growth by performing highly resolved simulations of a subset of the capsule solid angle. These treat nonlinear saturation and mode coupling in the presence of spherical convergence. We are interested in simulating the growth of the full spectrum of dangerous modes simultaneously to assess whether nonlinear mode coupling between high modes in the ablator drives up low modes, which could affect the capsule’s performance. Advances in the computing power available under the Accelerated Strategic Computing Initiative (ASCI) program have enabled us to model considerably larger solid angles than was previously practical. We consider here a simulation with a domain extending from $-36$ to $+36$ degrees in latitude and 72 degrees in longitude. The mesh measured $360 \times 360 \times 171$ zones in the two transverse directions and radial direction, respectively. The mesh motion algorithm ensures $0.7 \mu m$ radial zone spacing for all regions of the capsule shell that have interacted with the first shock. It has 18 transverse zones per wavelength for $l=100$. This mesh can resolve the growth of modes with $l \sim 2-100$ with good accuracy. Above $l=100$ the product of amplitude with growth factor is small enough that these modes should make only a small contribution to the resulting ablation front rms amplitude. Previous 2-D multimode simulations that included modes up to $l=160$ support this conclusion. Therefore, we believe this simulation resolves the full spectrum of the most dangerous modes which arise from surface roughness.

Figure 4 shows a schematic of the capsule simulated, which employs a beryllium ablator doped with 0.9% copper (BeCu). Its design parameters were specified by Dittrich. It is a variation of a design by Wilson. Other beryllium cap-

![Copper-doped beryllium ablator capsule.](image)

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FIG. 4. Schematic of copper-doped beryllium ablator capsule.
the discreet modes supported which have the closest effective \( l \) values from 1 to 100. Random phase factors are assigned to \( a_{mn} \) so that the topology of the surface does not have uncharacteristically large peaks and valleys. Contour plots of the actual perturbations initialized on the surfaces are shown in Figs. 5(a) and 5(b). The initial imposed RMS amplitudes are 20 nm for the ablator surface and 1.0 \( \mu \)m for the ice surface.

Figure 6(a) shows two iso-density contour surfaces from the simulation at 15.55 ns, near the time of peak implosion velocity. These surfaces are in the ablator and the inner boundary of the capsule wall. The prominent bubbles and spike sheets growing in the ablation front are described by mode numbers \( l = 60–90 \). Figure 6(b) shows similar surfaces at 15.65 ns, after the capsule has reached peak implosion velocity. The ratio of amplitude to wavelength in the ablator has increased largely due to the effect of convergence. The basic perturbation pattern persists through the implosion phase, indicating weakly nonlinear behavior. For implosions which successfully ignite, as does the present example, bubble merger\textsuperscript{32} is not a prominent feature in ablation front evolution. But nonlinear saturation and mode coupling are important. These high modes growing in the ablator can threaten shell integrity during the implosion phase, when the shell is thinnest, if they breach it before the peak implosion velocity is attained. In spite of the apparently large amplitudes in the ablator in Fig. 6(b), these perturbations can no longer reach the inside of the capsule as it rapidly thickens due to convergence. Bubbles rising on the inner shell surface have widths associated with a much lower range of mode numbers, falling in the range \( l = 10–20 \). The topology of the growing perturbations remains similar across the solid angle, showing no indication of significant low mode asymmetries driven by mode coupling. The capsule produces a robust yield of 15.4 MJ, compared with a 1-D clean yield of 17.0 MJ. The yield, along with the amplitudes and mode numbers of the dominant features in the capsule shell, resemble results from previous 3-D simulations performed over a 12 degree wedge with similar initial amplitudes,\textsuperscript{8} indicating those simulations were able to model the important nonlinear dynamics of the instability growth.

FIG. 5. (Color) Plots of surface perturbations placed on (a) inner ice and (b) outer ablator surfaces.

FIG. 6. (Color) (a) Density iso-con-tour surfaces of 13.8 g/cm\textsuperscript{3} at 15.55 ns. These bound the capsule shell. (b) Density iso-contour surfaces of 45 g/cm\textsuperscript{3} at 15.65 ns.
V. CONCLUSIONS

Many aspects of NIF target performance can now be modeled in three dimensions using HYDRA. Initial simulations of gas filled cylindrical hohlraums, including the capsule implosion, showed gas fill effectively controlled the hohlraum wall motion, which exhibited little deviation from axisymmetry in the main volume. For parameters used in these calculations the laser light was propagated successfully into the hohlraum for the required duration of the laser pulse. The radiation temperature in the hohlraum was essentially driven by nonlinear mode coupling.

There was no evidence of anomalous low mode growth in dynamic instabilities evolved into the weakly nonlinear regime. There was no evidence of anomalous low mode growth driven by nonlinear mode coupling.

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