Shock Physics with the Nova Laser for ICF Applications


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The physics of high pressure shocks plays a central role in Inertial Confinement Fusion (ICF). In indirect drive ICF, x-rays from a gold cavity (hohlraum) are used to ablatively drive a series of high pressure shocks into a spherical target (capsule). These shocks converge at the center, compressing the fuel and forming a hot dense core. The target performance, such as peak fuel density and temperature and neutron yield, depends critically on shock timing, and material compressibility.

A typical target for the proposed National Ignition Facility (NIF) is composed of an outer ablator and an inner fuel region (Figure 1).1

The ablator is typically CH, Be or B₄C. The first two materials require doping with a high-Z material (Ge, Br, Cu) in order to minimize x-ray preheat of the DT fuel. The fuel region is a frozen layer of DT on the inner wall of the ablator. The NIF x-ray drive, which consists of a two step "foot" (~80 eV and ~120 eV) followed by a ramp up to a peak (~300 eV), drives multiple shocks into the ablator with pressures in the range from ~1-300 Mbar (Figure 2). Proper timing of the shocks, to better than 10%, is crucial to minimize the fuel entropy and maximize the capsule neutron yield. The two simulations shown in Figure 2 illustrate this sensitivity: advancing the timing of the "ramp" section of the drive 0.5 ns from the optimal design advances the third shock 0.5 ns and increases the fuel isentrope by roughly a factor of 2 during the compression phase of the implosion (Figure 3) which ultimately results in a factor of ~50 reduction in neutron output. Clearly, an accurate knowledge of the EOS and opacity of these materials is an essential part of designing and modeling NIF experiments.
Figure 2. Optimal radiation drive and fuel pressure vs time for a particular NIF capsule design (solid). Also shown is the same drive shifted earlier by 0.5 ns during the rise following the "foot" (dashed).

Figure 3. Resulting fuel isentrope for the optimal and shifted drive during compression. The target with optimally timed drive reaches higher density at a given pressure.

Extensive experimental measurements of the EOS of materials have been performed in the so-called "normal" or "experimental" pressure region below 1 Mbar. At very high pressures, P>1 Gbar, Thomas-Fermi-Dirac theory applies. In the "intermediate" region, from 1-1000 Mbar, pressure and temperature ionization effects are important and the theoretical treatment is more difficult. Experiments on existing large laser facilities are able to produce shocks in this pressure region, allowing direct comparison of the shock strength in typical ablator materials to calculations. To improve our accuracy in predicting NIF target performance, we perform a range of experiments on the Nova laser to test our understanding of the important physical processes. Specifically, we study; 1) shock strength in typical ablator materials, and 2) hydrodynamic instabilities in ablatively accelerated targets. In this proceedings article we summarize two techniques for determining properties of x-ray driven shock in typical target materials.

Indirect drive experiments on Nova are performed by heating a cylindrical gold hohlraum (typically ~3 mm long and 1.6 mm in diam.) with a total of ~ 30 kJ of 351 nm light (Figure 4). The ten Nova beams are directed into the hohlraum though holes in the ends, typically 1.2 mm diameter. The laser energy is absorbed in the high-Z wall and reradiated as x-rays, producing a uniform and nearly Plankian source with radiation temperature, $T_R \sim 225$ eV. Radiation temperatures up to ~300 eV have been achieved using smaller scale hohlraums. A target exposed to this x-ray drive inside the hohlraum is strongly shocked by the pressure generated from of the ablating target material. The shock pressure can be roughly estimated as:

$$p = \frac{1}{2} \frac{\sigma T_R^4}{RT_R} \frac{1}{\mu},$$

where $T_R$ is the radiation temperature, $\sigma$ and R are the Stefan-Boltzmann and gas constants respectively, and $\mu$ is the mean molecular weight per free particle, $\mu = \frac{A}{Z+1}$. For fully ionized CH ($m = 13/9$), $p(\text{Mbar}) = 2 \times 10^4 T_R(\text{keV})^{3.5}$. Typical radiation temperatures on Nova hohlraums therefore produce shocks with peak pressures of ~ 100 Mbar in plastic targets.
In our experiments we directly measure the x-ray driven shock strength in typical ablator materials by observing the shock transit time through a slab of the material that is mounted over a hole in the side of the hohlraum (Figure 4). The slab is made with "steps" of known thickness or as a wedge of increasing thickness, providing a range of the shock transit times for different times during the duration of the x-ray drive. The breakout of a shock on the rear side of the ablator material results in a flash of ultraviolet light from the shock heating of the material on the rear surface to ~10 eV. The UV light is recorded by a streak camera coupled to a Cassegrain telescope which images the emission onto the slit of the streak camera. The accuracy of the shock velocity measurement is ~2%.

Typical data from the shock breakout through a wedge shaped sample of CH doped with 3% Br is shown in Figure 5. This material is currently used on Nova targets as an ablator for NIF-like implosion experiments. In this measurement, the hohlraum was driven with a time varying laser pulse, resulting in the radiation temperature shown in Figure 6. The calculated shock break out time from LASNEX is shown overlaid on the measurement in Figure 7.

Figure 4 Schematic of hohlraum target. X-rays from the laser heated cavity ablate material from a sample or target exposed to the drive, driving a strong shock into the material.
Although this technique provides a direct measurement of shock timing for a given laser drive, which is ultimately what is required for tuning a NIF capsule to reach ignition, it does not directly measure the EOS of the material because of uncertainties in the ablator opacity and consequently the ablation pressure. In some cases, such as predicting the compression of the DT ice during the "foot" of the NIF pulse, it is desirable to measure just the EOS. Recent calculations for D$_2$ ice, that include molecular dissociation, indicate a softer EOS than earlier calculations for pressures in the 1-10 Mbar regime. This softer EOS predicts a higher fuel density during the "foot" of the NIF drive and results in a significant increase in ignition margin in current designs. The EOS of ablator materials is also important in determining the evolution of hydrodynamic instability growth (Richtmyer-Meshkov and Rayleigh-Taylor), of initial ablator and DT ice surface imperfections.

The EOS can be isolated by conducting experiments where two materials are driven side-by-side, a "test sample" of interest and a "reference standard" such as Al. These experiments would use a common ablator material to generate an equivalent shock into both materials. This so-called "impedance matching" technique relies on the fact that the shock pressure $P$ and the particle velocity, $u_p$, are conserved when the shock crosses from one material into another. By applying an equivalent steady pressure to both materials, a point on the Hugoniot of the "test sample" can be inferred from the shock velocity, $u_s$, through the "sample" and the "standard", if the initial conditions are known. Accurate measurements, however, place very strict requirements on shock planarity and steadiness, and x-ray preheat. In addition to standard ablator materials, these experiments could also be performed with frozen D$_2$ as the "sample".

An alternative technique that may be useful for determining the EOS of target materials is x-ray radiography. In this approach, a shocked sample is backlighted with x-rays, produced by focusing one or two beams of the laser, delayed relative to the drive beams, onto a backlighter disk. Shock compression of the sample increases the areal density, and consequently the optical depth, through the package in the viewing direction, resulting in a decrease in the transmitted backlighter x-ray intensity. A series of radiographic images yield the position of the shock front in the material as a function of time and hence the shock velocity. For probing solid density ablator materials, with typical sample dimensions of ~1mm, the backlighter is typically a metal disk, resulting in K-shell x-ray emission in the 4-7 keV spectral region. For a ~1 mm solid D$_2$ sample, the optimum backlighter energy is ~1 keV.

A radiographic image of an indirectly driven target is shown in Figure 8. In this experiment, we ablative drove one end of a plastic (CH) cylindrical sample (0.5 - 0.7-mm diam and 1.5-mm in length) with x-ray drive and observed the shock propagate into the material. These samples were mounted from the wall of the hohlraum as shown in Figure 2 and were viewed from a direction perpendicular to their length, and therefore transverse to the axial direction of shock propagation. The radiographic images were recorded with an
8x magnification pinhole camera coupled to a gated microchannel plate detector, providing 16 time-resolved "snapshot" x-ray radiographs of the sample.10 The position of the shock front is clearly visible. In this experiment a thin (150 μm diam.) Al wire was located on the axis of the cylindrical plastic sample for preliminary experiments on shear flow.11

Figure 8. An x-ray radiographic "snap-shot" image of a shock propagating into a cylindrical plastic sample. The shock is driven by x-ray ablation from above. This sample has an aluminum wire embedded along its axis for a series of experiments aimed at studying shear flow. The compression of the plastic is seen as a region of decreased x-ray transmission (darker) behind the shock front. The shock pressure was ~12 Mbar at the time that this image was recorded.

A quantitative measurement of the transmission through the shock compressed region, along with knowledge of the cold opacity of the material, yields the compressed density.12 The particle velocity can also be measured by doping a region of the material with a small amount of high-Z material so that it is radiographically opaque, or by imaging the position of an opaque pusher. For the case of a steady shock, knowledge of both the shock and particle velocity provides an independent measurement of the compression of the shocked material.

To test existing EOS models for D2 we are planning a series of experiments to measure the shock speed and compressed density of D2 ice in the 1-10 Mbar regime. Since the predicted difference in shock speed for current models differs by at most 1-2% we are investigating the possibility of extending optical interferometric techniques used extensively in the gas gun community to laser driven shocks. We have considered both standard Michelson interferometers13 and VISAR (velocity interferometer system for any reflector)14 techniques. Along with being able to measure shock speed to the necessary accuracy to impact our models, these techniques allow us to accurately quantify shock planarity and steadiness which have historically been a primary concern in laser shock wave experiments.

Although the shock speed differences between current EOS models for D2 are small, the predicted compression differs by as much as 20%. To directly measure the compression we must optimize our radiographic techniques. The accuracy of radiography measurements is primarily determined by the spatial resolution of the imaging diagnostic. In the radiographic measurements described above, hard x-ray imaging was necessary to penetrate the target and consequently pinhole optics with spatial resolutions of ~10 μm were used. The optimal backlighting energy for D2 is ~1 keV, which allows us to use multi-element imaging systems that have the potential for 1-3 μm resolution. An aberration corrected Kirkpatrick-Baez microscope with 3 μm resolution has already been demonstrated by a group at OSAKA15. Another option is to design a multilayer coated aspherical mirror system that can operate at higher angles. Since we can tolerate some astigmatism it should be possible to achieve the necessary spatial which a single mirror system. We estimate that density measurements with accuracies of better than 5% should be possible with these radiographic techniques.

Summary
Accurate predictions of NIF target performance depends critically on shock timing and material compressibility. Current measurement techniques enable us to accurately determine shock timing in planar samples of ablator material as a function of laser drive. Although this technique does not separately address uncertainties in material EOS and opacity, it does allow us to tune the laser drive until the desired shock timing is achieved. Experiments to directly address the EOS of D₂ ice are planned to further increase the margin for ignition in current target designs.

1. Haan, LANL, reference?
5. High T reference
6. See National Technical Information Service document no DE 92006882,
7. N. Holmes, these proceedings
8. S.V. Haan, private communication
12. ibid
15. Kodama et al.