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An assessment of the 3D geometric surrogacy of shock timing diagnostic techniques for tuning experiments on the NIF*

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Abstract. Ignition capsule implosions planned for the National Ignition Facility (NIF) require a pulse shape with a carefully designed series of four steps, which launch a corresponding series of shocks through the ablator and DT ice shell. The relative timing of these shocks is critical for maintaining the DT fuel on a low adiabat. The current NIF specification requires that the timing of all four shocks be tuned to an accuracy of $\leq \pm 100$ ps. To meet these stringent requirements, dedicated tuning experiments are being planned to measure and adjust the shock timing on NIF. These tuning experiments will be performed in a modified hohlraum geometry, where a re-entrant Au cone is added to the standard NIF hohlraum to provide optical diagnostic (VISAR and SOP) access to the shocks as they break out of the ablator. This modified geometry is referred to as the “keyhole” hohlraum and introduces a geometric difference between these tuning-experiments and the full ignition geometry. In order to assess the surrogacy of this modified geometry, 3D simulations using HYDRA [1] have been performed. The results from simulations of a quarter of the target geometry are presented. Comparisons of the hohlraum drive conditions and the resulting effect on the shock timing in the keyhole hohlraum are compared with the corresponding results for the standard ignition hohlraum.

1. Hohlraum geometry for shock tuning experiments on the NIF

The current plan for experimentally tuning the shock timing on NIF is to perform a small number of full-scale, no-yield shots using a diagnostic variation of the standard NIF hohlraum, which has become known as the “keyhole” hohlraum. A schematic showing two variations of this target is given in Figure 1(a). The geometry for tuning the first three shocks is shown on the left. In this geometry, a gold re-entrant conical tube enters through the hohlraum wall into the interior of the capsule. The tip of this cone, which is located just inside the ablator inner surface, has a $260\mu\text{m}$ diameter aperture, and the other end outside the hohlraum is sealed with a very thin, optically transparent quartz window. The full volume inside the capsule and Au cone is filled with liquid deuterium, which provides a good surrogate to the shock propagation in the DT ice layer, which will be present in full ignition targets. In this geometry, the VISAR diagnostic reflects from the leading shock to diagnose both the shock strength (velocity) and the coalescence times and radii of the first three shocks. The nominal goal is to

position the first three shocks so that they coalesce at a radius about $5\ \mu\text{m}$ inside of the DT ice / DT gas interface in the full ignition target (see Figure 3(b) for an example of the shock trajectories). This technique, which has been successfully demonstrated on the Nova laser [2], is expected to be viable through the time of coalescence of the first three shocks. Beyond this time, however, the VISAR window is expected to become opaque due to the extreme radiation environment present in the hohlraum. Experiments under way at Omega have thus far demonstrated window viability to 180eV, which is just sufficient for diagnosing the timing of the third shock.

The right-hand side of Figure 1(a) shows a slight modification of the keyhole target design that looks promising for tuning the 4th shock timing [3] using the Streaked Optical Pyrometer (SOP), which is part of the VISAR optical system. The SOP uses the same optics and cross-timing system as the VISAR, which will be essential in minimizing experimental timing offsets between the time at which the first three shocks coalesce (again, see Figure 3(b)) and the time at which the 4th shock merges with this combined shock. This diagnostic geometry again uses the same re-entrant Au cone, but with a minor modification at the tip inside the capsule to include an optically opaque layer of material. This layer, which is spherically symmetric with the ablator, essentially forms an inner shell. Liquid deuterium is now required only between the ablator inner radius and this diagnostic inner shell layer at the tip of the re-entrant cone. The VISAR window, which was problematic at the late-time, high radiation temperature conditions in the hohlraum, is now no longer needed. The SOP will be used to measure the time at which the final combined shock (shocks 1-2-3 merged with shock 4) breaks out of this diagnostic layer.

In order to assess the surrogacy of this modified hohlraum geometry, 3D simulations using HYDRA [1] have been performed. Figure 1(b) shows a pair of simulation geometries that were used to assess the differences in hohlraum drive conditions resulting from the presence of the Au diagnostic cone. In both simulations, all capsule and hohlraum dimensions as well as laser pulse shapes, energies, and beam spatial patterns are taken from the NIF Rev. 1 specification. The only difference between the two simulations is the Au cone, which for these initial simulations stops at the ablator wall and does not enter the capsule interior. A quarter of the full hohlraum geometry is simulated in each case. Symmetry boundary conditions are used at the equatorial plane and the hohlraum mid-plane. This introduces an artificial symmetry in the laser beam illumination, which does not exist in the full hohlraum. In a full hohlraum, for example, inner cone beams from opposing LEHs (laser entrance holes) are not symmetric, but rather are rotated by 45° . This introduces a drive difference when comparing to a complete hohlraum simulation, but for the present purpose, we will only be comparing the two quarter-geometry simulations, which both have the same modified illumination pattern.

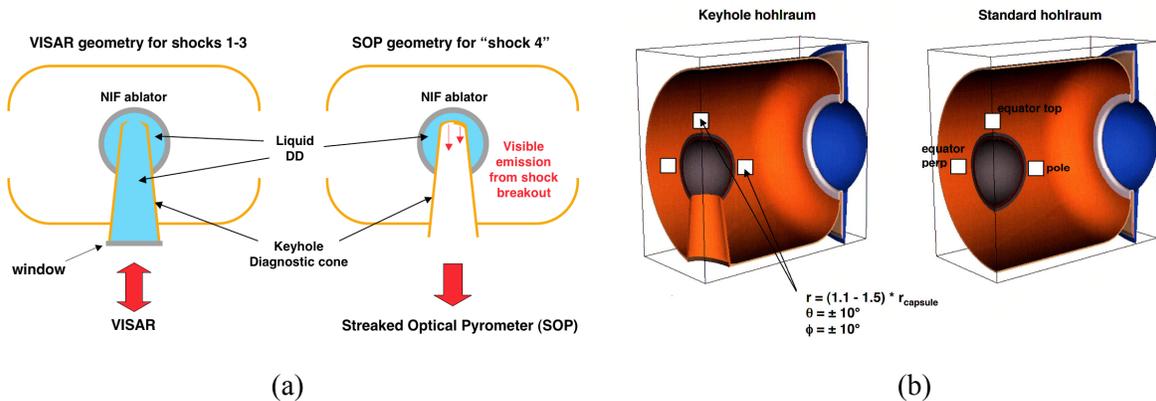


Figure 1. (a) Schematic drawing of keyhole hohlraum. (b) HYDRA simulation geometry for keyhole vs. standard hohlraum

2. Results from 3D HYDRA simulations of $\frac{1}{4}$ of the “keyhole” hohlraum

Figure 2(a) shows a comparison of the radiation temperature field in the keyhole vs. the standard hohlraum simulations at a time of 4ns, which is approximately the middle of the “foot” or first step in the laser power history. The color scale spans the range from 0-100eV. Several of the laser spots can clearly be seen at the hohlraum walls. In the equatorial plane, 4 spots are seen in this quarter of the hohlraum. If this were a complete 3D simulation with a second LEH, there would be an additional set of laser hot spots in between each of these spots due to the 45° rotation between the inner cone beams entering from opposing LEHs. The radiation temperature distribution in the two simulations is nearly identical with the exception of the location near the bottom of the Au cone, where a few quads directly illuminate the cone. At the top of the capsule, however, where the shocks will be diagnosed, there is no visually observable difference in the drive.

Figure 2(b) shows a comparison of the electron temperature field between the two simulations at a significantly later time, $t = 12\text{ns}$, which is approximately the time of peak laser power or midway up the 4th and final step in the T_R history. At this point in time, all 4 shocks have been launched into the ablator, and subsequent changes have little effect on the shock timing. The plasma conditions appear very similar throughout the hohlraum, again with the exception of the base of the Au cone. The differences remain confined to a small region near the cone.

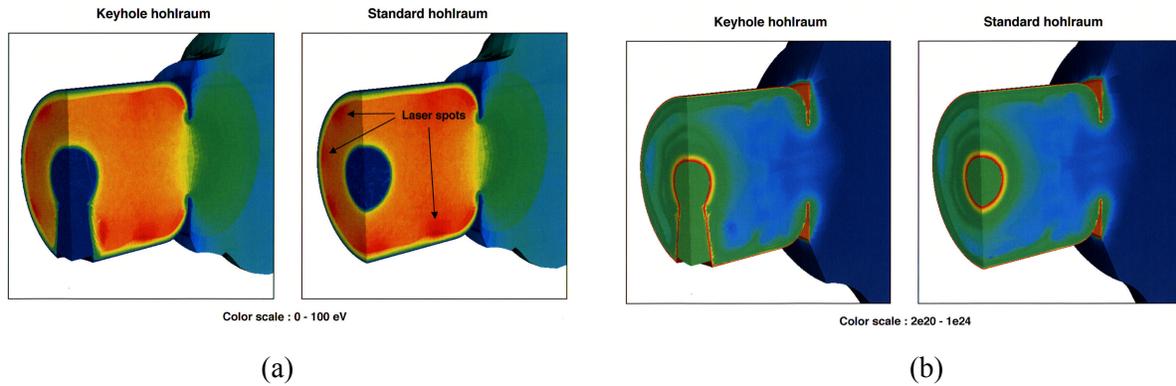


Figure 2. (a) Comparison of radiation temperature field at $t = 4\text{ ns}$ (middle of first step in T_R history). (b) Comparison of electron density field at 12 ns (middle of final rise to peak T_R).

3. Assessment of the effect the keyhole geometry on the timing of the shocks

In order to quantitatively compare the hohlraum conditions, a volume-averaged T_R history has been extracted locally at the pole and two perpendicular locations on the equator from each simulation. The location of each of these T_R histories is shown in Figure 1(b). In each case the T_R history is averaged over a volume that extends from 1.1 to 1.5 times the initial ablator radius and $\pm 10^\circ$ in both theta and phi. In the case of the primary diagnostic view at the top of the equator, this angular extent is very similar to that sampled by the aperture at the tip of the cone.

Figure 3(a) shows plots of the T_R history in each of the four drive steps. In each plot, 6 curves are shown. The solid lines give the T_R history from the keyhole (KH) simulation, and the dashed lines are from the standard geometry (no KH). The results extracted at the pole are shown in red, the top of the equator in green, and the perpendicular view at the equator in blue. Overall, the T_R histories are very similar, both in position around the capsule and between the two simulations, never varying by more than a few eV. For the primary diagnostic view at the top of the equator, the difference between the keyhole and the standard hohlraum is at all times less than $\sim 1\%$ in T_R or less than 4% in radiation flux driving the implosion. During the foot, the KH simulation (at the equator, top) is about 1eV lower

than the no KH simulation. The two are nearly indistinguishable during the 2nd plateau. For the 3rd and 4th steps, the KH simulation is about 1eV higher than the no KH simulation.

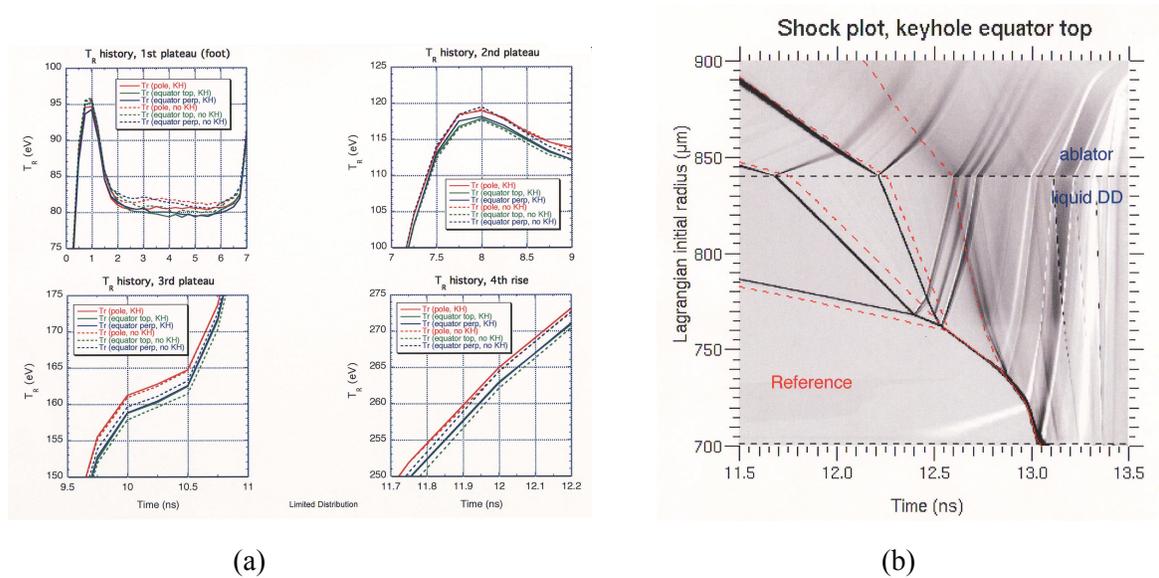


Figure 3. (a) Comparison of T_R histories in each of the 4 steps. (b) Lagrangian shock plot at the equator top comparing keyhole simulations (black) vs. no keyhole reference (red)

The T_R histories of Figure 3(a) have been used as a drive source for more highly-resolved 1D simulations to assess the effect of the keyhole cone on the shock timing. Figure 3(b) shows a plot of the shock trajectories as a function of the Lagrangian initial radius and time. The red dashed lines give the shock trajectories in a nominal 1D simulation for reference. Note that by design, the first three shocks coalesce at a single point. The black curves (visualized by a contour plot of radial pressure gradient) give the result of a second 1D simulation, where the drive is the nominal drive multiplied by a time-dependent flux multiplier obtained from the ratio of the flux in the simulation with the keyhole to that without the keyhole. These trajectories, therefore, give the difference from a nominal implosion due to the presence of the diagnostic cone. From Figure 3(b), it is seen that the keyhole simulation results in a 1st shock that breaks out from the ablator about 90ps late, but propagates with nearly identical velocity to the no-keyhole reference simulation. The 2nd shock breaks out slightly earlier than the nominal, resulting in a merger of shocks 1-2 that is 160ps earlier and at a radius 7 μm greater than nominal. A smaller difference is seen for the merger of the 3rd and 4th shocks.

The bottom line is that this timing difference resulting from the diagnostic geometry is comparable to values that are consistent with the Rev. 1 specification, which allows for a 5% uncertainty (due to laser variations, hohlraum physics uncertainty, etc) in the capsule flux. We would like the diagnostic-related timing difference to be smaller than this, however. It is expected that full 3D simulations with the correct beam illumination will show a further improvement in the surrogacy of this geometry.

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