Hohlraum Radiation Drive Measurements on the Omega Laser

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Time-resolved drive measurements with thin-walled hohlraum targets on Omega [J. M. Soures *et al.*, Phys. Plasmas **3**, 2108 (1996)] are presented and compared with two-dimensional hydrodynamical simulations. For the first time, radiation fluxes are measured through the laser entrance hole instead of through a diagnostic side hole. We find improved agreement between time dependent experiments and simulations using this new technique. In addition, the drive history obtained in this manner correlates well with the drive onto the capsule at target center. [S0031-9007(97)03855-6]

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In the laser driven indirect drive fusion scheme [1], laser beams are focused through the laser entrance holes (LEH) onto the inside wall of a high-Z enclosure or hohlraum. The laser light is absorbed and converted into soft x-rays that fill the hohlraum and heat a target capsule in the center. As the x rays heat the capsule, rapid ablation occurs, and outward expansion of the capsule material causes a rocketlike reaction that leads to an implosion of the central capsule material. For this reason, the x-ray radiation is referred to as the "drive." Detailed knowledge of the radiation drive is of great interest and has been the objective of many hohlraum experiments over the last decade [2–6]. The radiation is often characterized by a radiation temperature T_r, which is defined by equating the total frequency integrated radiation flux to a blackbody flux σT_r^4, where σ is the Stefan-Bolzman constant.

Time-dependent radiation temperatures have been measured extensively on the Nova [7] laser using an absolutely calibrated filtered diode array called Dante [4,8,9]. In the Nova experiments, the Dante diagnostic was set up to measure the radiation flux emerging from a hole in the side of the hohlraum with a Dante angle (θ_D in Fig. 1) of 90°. Since this method only measures the radiation flux coming off the indirectly heated wall opposite the hole, the flux must be divided by the wall's effective reflectivity, or "albedo," to obtain the true radiation temperature near the wall [4,9]. The albedo depends upon the material opacity, which varies with time, and must be calculated analytically or numerically. Peak temperatures measured through the "side hole" agree well with simulations [9]. However, the simulations underestimate the drive at early times. This discrepancy has been attributed to uncertainties in the low temperature opacities and to scattered or reflected laser light hitting the portion of the wall being measured. The opacity is determined using an average atom model called XSN [10]. At high temperatures ($>$200 eV), wall losses modeled with XSN are quite close to those calculated with a more sophisticated STA [11] model and with experiments [12]. However, XSN opacity multipliers of 1.5 are needed to agree with the statistical-transition-array estimates at lower temperatures ($<$150 eV) [13]. The early time drive could also be recovered using a 1.5 multiplier on XSN opacity and allowing 10% of the laser light to strike the wall, or by using a factor of 3 multiplier with no incident laser light.

Recently, proof-of-principle hohlraum experiments have been performed on the Omega laser facility. Up to 40 of the 60 beams were used to irradiate Nova-scale hohlraums with up to 20 kJ of 351 nm wavelength light delivered in a 1 ns flat top pulse [14]. Unlike experiments on Nova with a single laser cone at an angle of 50° relative to the hohlraum axis, the laser beams on these experiments are distributed into three cones at angles of 21°, 42°, and 59°. In addition, thin-walled hohlraums are used to limit debris in the chamber and allow imaging of both laser spots and imploded cores [15]. These hohlraums are constructed from 2 μm gold walls with 100 μm of CH overcoat for structural support.

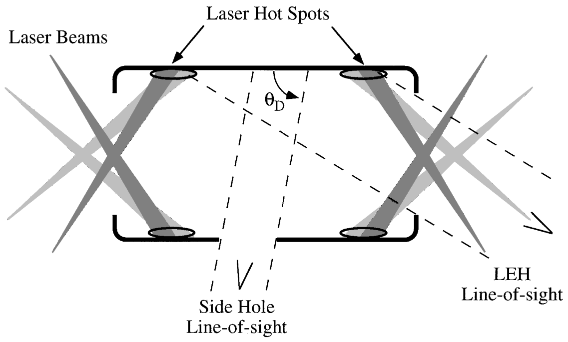

FIG. 1. Laser fusion hohlraum showing Dante diagnostic line of sight through the side hole and the LEH.

The inside diameters are 1600 μm and the lengths varied from 2100 to 2800 μm. Some of the hohlraums had 500 μm diameter diagnostic holes drilled in their sides.

In this Letter we report on drive measurements and present two-dimensional Lasnex [16] simulations of these experiments. Details about hohlraum simulations with Lasnex can be found in Ref. [5]. In order to make a connection to previous Nova experiments, measurements were done using the traditional side-hole technique [4]. However, we also measured the radiation flux through the LEH for the first time. The experimental results, as well as simulations, indicate that drive measurements through the LEH are superior to those through the side hole. There is good agreement between experiment and simulation. In particular, there is no longer the early time discrepancy seen on previous Nova experiments. In addition, simulations suggest that the radiation flux emerging from the LEH may be more representative of the drive on the capsule. The reason for this last point is that in our experiments the line of sight through the side hole only samples the indirectly heated wall, while the line of sight through the LEH, like the capsule, sees both walls and laser hot spots (see Fig. 1).

The Dante diagnostic [8] which measures the radiation flux is a ten channel array of absolutely calibrated x-ray vacuum photodiode detectors, using photocathodes of Al, Cr, and Ni. Various thin filters and grazing incidence mirrors are placed in front of the detectors so that each channel has a significant response in different parts of the spectrum. The total spectral coverage ranges from 50 to 3000 eV. The diodes' outputs are recorded on 5 GHz bandwidth oscilloscopes, and the system has a temporal response of order 200 ps. The data are analyzed, at 100 ps intervals, to find a smoothed spectrum which is consistent with the signal from each channel. Because the channels have some overlap in their spectral coverage, the problem is well constrained, and while some variation is possible in the details of the spectrum (by varying the amount of smoothing allowed), the integral over all energies varies little with these variations. This flux (in watts per steradian, from a hole of known area and view angle) is conveniently characterized by a radiation temperature T_r, as described earlier, even though the smoothed spectrum is not necessarily Planckian (we show measured spectrum below). To ensure that Dante only collects radiation along the direct line of sight, shots with no diagnostic side hole were performed to verify that negligible amounts of radiation reach the Dante diagnostic through the thin Au walls.

In some of the drive measurements, the radiation temperature was measured through the side hole ($\theta_D = 79°$ in Fig. 1). The hohlraums were 2800 μm in length and shot with 15 kJ of energy using the two laser cones at 42° and 59°. Since on Nova, T_r is only measured through the side hole, complementary experiments to Omega were performed on Nova using identical thin-walled hohlraums at similar laser power. The T_r measured on both Omega and Nova thin-walled hohlraums along with the simulated temperatures are shown in Fig. 2. The 10 eV difference between the Omega and Nova shots is due to beam pointing. The Omega T_r is colder because the laser spots are farther from the midplane area where Dante views. This 10 eV difference is predicted by the simulations as well as with simple view-factor calculations. At early time, comparison of the data to simulations for the thin-walled hohlraums is similar to that of earlier thick-walled (25 μm Au wall) Nova hohlraums [9]; namely, simulations underestimate the early time temperature. However, we found that the peak temperatures from thin-walled hohlraums on both Omega and Nova were consistently 10–20 eV below the predicted value. This result is in contrast to thick-walled Nova hohlraums where the simulated peak T_r was always within a few eV of the experiment [4,9].

From these thin-walled experiments it may appear that the thin-walled hohlraums are cooler than their thick-walled counterparts [4,9]. However, simulations of Au wall thicknesses of 2 and 25 μm give identical radiation temperatures. This result is consistent with simple estimates [1] showing the burn-through time for 2 μm of Au at $T_r = 200$ eV to be on the order of 2 ns which is longer than the laser pulse duration. Moreover, as we will show below, temperature measurements through the LEH are indeed as hot as predicted. We now believe that the discrepancy between peak T_r measured through the side hole is due to hole fabrication rather than wall thickness. On the thick-walled hohlraums used in previous Nova experiments, the side holes were lined with beryllium washers to prevent hole closure. In contrast, the side holes on the thin-walled hohlraums were constructed by simply drilling straight through the 100 μm CH and 2 μm Au wall. This type of construction is more

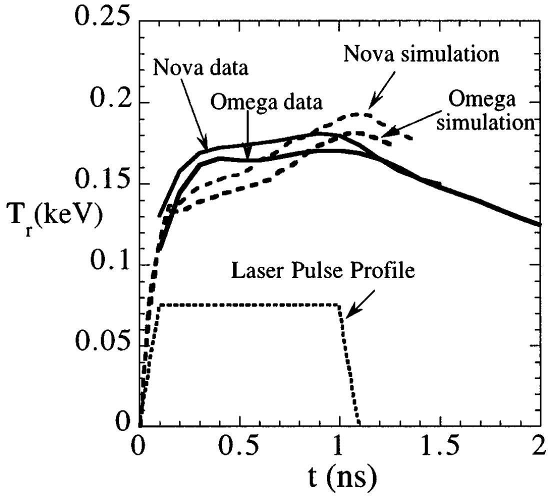

FIG. 2. Radiation temperature seen through the side hole (solid line) along with the Lasnex simulation (dashed line) from both Omega and Nova experiments.

susceptible to hole closure and tunnel obstruction effects. Experiments have recently been performed on Nova using thick-walled hohlraums with hole construction similar to the thin-walled hohlraums. The peak temperatures were consistently 10–12 eV below predictions. The experiments clearly show that hole fabrication has an effect on the measurements. However, rather than dwelling on improvements to the diagnostic side hole, we chose to investigate a new method of measurement.

The new method we chose was to measure the radiation temperature through the LEH. Because of the "soccer ball" symmetry of Omega [17], there are many orientations of the hohlraum that give an identical laser irradiation pattern on the hohlraum. In one orientation we used, the Dante diagnostic viewed through the LEH at an angle of 37.4°. Besides measuring a flux more representative of the capsule drive, there are several practical advantages of measuring radiation fluxes through the LEH. First, the LEH is 2.5 times larger than the diagnostic hole, and therefore, hole closure should be less significant. Second, this method is less invasive. A hole in the side of the hohlraum disturbs the cylindrical symmetry (which is amenable to 2D modeling) and adds to the radiation losses. Third, the laser heated blowoff in the LEH is hotter and less dense than blowoff in the side hole. This effect should make the LEH blowoff more transparent to the x-ray radiation we wish to measure. Fourth, LEH measurements can be made simultaneously with implosions. Typically, capsules block Dante's view of the wall opposite the side hole. Finally, viewing the laser hot spots gives a better measurement of hard x rays. In Figs. 3(a) and 3(b) we plot the radiation temperatures measured through the LEH along with the corresponding simulated data for hohlraum lengths of 2100 and 2300 μm, respectively. Both of these shots had 15 kJ of energy and used cone angles of 42° and 59°. There is very good agreement between simulations and experimental data over the duration of the laser pulse. In particular, there is good agreement at early times. At 300 ps the simulated and measured temperatures agree to within 5 eV. By comparison, there is a 20 eV discrepancy when measured through the diagnostic hole in the side on the hohlraum as described above. In the inset of Fig. 3(b) we plot a typical measured spectrum to show the non-Planckian distribution due to line emission in the coronal plasma.

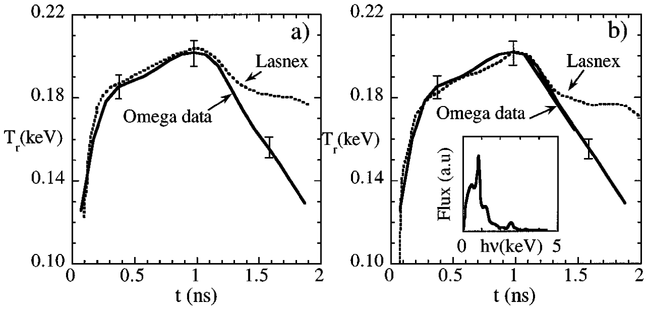

FIG. 3. Radiation temperature seen through the LEH (solid line) along with the Lasnex simulation (dashed line) for hohlraum lengths of (a) 2100 μm and (b) 2300 μm. Inset: Spectrum of radiation flux at 1.0 ns. Error bars show typical 3% uncertainty in T_r for Dante measurements.

The good agreement between measurements through the LEH and the simulations, during the duration of the laser pulse, indicates that we are accurately modeling the laser hot spot physics. When viewing the 2100 μm hohlraum at 37° through the LEH, there are six laser spots which constitute 28% of the observed wall area, which in turn is 12% of the total wall area. However, simulations show that the laser hot spots account for over 70% of the flux at $t = 300$ ps. Therefore, at early times the radiation flux seen by the capsule and through the LEH is dominated by the laser irradiated hot spots. At peak drive, the flux from the indirectly heated wall exceeds that from the hot spots. There is still good agreement up to 1.3 ns because the indirectly heated wall is hot and modeled correctly. Beyond this time, modeling and experiment diverge. However, it is difficult to explain, with arguments based on energetics, how a hohlraum could continue to cool so rapidly. For this reason, we suspect that this late time discrepancy may be related to opacity modeling in the rapidly cooling plasma accumulating at the LEH. More sophisticated opacity models [11] indeed show that the plasma in the LEH becomes more opaque in the thermal x-ray region than predicted by the XSN model used in the simulations.

We now examine how the drive seen on the capsule compares to that seen through the LEH with simulations. We consider a 2100 μm hohlraum being driven by 15 kJ laser at cone angles of 42° and 59°. In Fig. 4 we plot the simulated temperature of the flux on the capsule; flux through the LEH at 37.4°; flux through the side hole; and

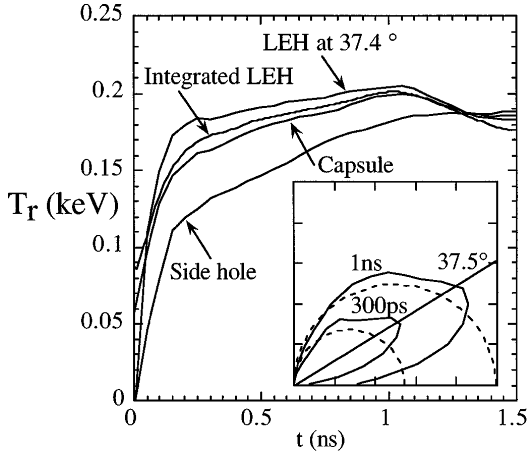

FIG. 4. Comparison of simulated $T_r(t)$ of the flux onto the capsule, through the LEH at 37.4°, total flux (integrated over all angles) out of the LEH, and through the side hole. Inset: Radiation flux out of the LEH (in arbitrary units) versus angle at 2 times. Also shown are the equivalent Lambertian flux (dashed line).

total flux (integrated over all angles) out of the LEH. This plot shows that the total LEH flux would provide the closest measurement to capsule drive. Next closest is the single line of sight LEH measurement at 37.4° which is a bit higher than the capsule flux but much closer than the single line of sight through the side hole. In general, inferring true capsule drive from any single line of sight requires albedo/geometry corrections. However, the single line-of-sight LEH measurement requires less correction, and the simulated and experimental temperatures are in much better agreement. It is for these reasons that we believe temperature measurements through the LEH are more representative of the drive on the capsule.

Last, we look at the angular dependence of the radiation flux ($\sim T_r^4$) through the LEH. The solid lines of the inset of Fig. 4 are polar plots of the intensity/sr at 300 ps and 1 ns (arbitrary units) emerging from the simulated LEH. For contrast, the dashed lines show Lambertian intensity/sr with the same integrated power (171 and 199 eV). A Lambertian intensity assumes a uniform wall temperature—the angular dependence comes from the projected hole area, i.e., $\cos\theta$. At small polar angles, where the diagnostic would view the opposite LEH, the simulated LEH intensity/sr is much less than the equivalent Lambertian. The intensity rises rapidly as the line of sight begins to view an admixture of reemitting wall and hot spots. The simulated intensity/sr then drops roughly as the cosine of the polar angle since the projected area of the LEH decreases at larger angle. At later times, when the wall albedo has risen and the emission is not so dominated by hot spots, the intensity/sr about 25° is approximately Lambertian. Consequently, any angle greater than this would provide a measurement which is fairly representative of the total radiation energy escaping the LEH. At earlier times, when the hot spots dominate, the intensity/sr has more structure. A better diagnostic technique, especially at earlier times, would be to measure emission at several angles, thereby allowing us to properly perform the angular integration. We have long term plans to develop such a diagnostic array.

In summary, measuring the radiation drive through the LEH appears to be a much better diagnostic of drive than measurements through a side hole. Unlike the side hole, closure, uncertainties in the low temperature opacity, and stray laser light do not appear to be a problem. Moreover, the raw (uncorrected) temperature is more representative of the capsule drive. We plan to further develop this method for measuring future hohlraums such as those for the National Ignition Facility.

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