Towards a more universal understanding of radiation drive in gas-filled hohlraums

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Abstract. We have found that radiation-hydrodynamic calculations that use the high flux model assumptions [1] can accurately predict the radiation drive produced by a laser-heated hohlraum under certain conditions, but can not predict drive over a broad range of parameters (pulse energy, hohlraum gas fill density, hohlraum case-to-capsule ratio). In particular, the model is accurate for ~7 ns long laser pulses used to implode capsules with high density carbon (HDC) ablators in hohlraums with helium fill gas densities of 0-0.6 mg/cc. By systematically varying the gas fill density from 0 to 1.6 mg/cc we found that the agreement with drive begins to diverge for fills > 0.85 mg/cc. This divergence from the model coincides with the onset of measureable SRS backscatter. In this same set of experiments the radiation drive symmetry inferred from the imploded shape of a gas-filled capsule is not predicted with this model. Finally, several possible fixes to the model to reduce the observed discrepancies are considered.

1. Introduction

To correctly model x-ray production and symmetry from a laser-heat hohlraum a number of physical processes must be included. These processes include laser absorption via inverse bremsstrahlung and heating of the plasma, thermal transport from the coronal plasma to the denser, cooler wall plasma, conversion of thermal energy to x-rays, expansion and dynamics of the ablated wall and ablator plasmas, the dynamics closure of the laser entrance hole, and laser plasma interactions, including backscatter and cross beam energy transfer (CBET).

We have developed a standard model in the radiation-hydrodynamics code Hydra [2] for calculating laser-driven hohlraum experiments. For an axisymmetric calculation we use about 34,000 zones, 85 photon energy groups, and 5 million IMC photonics particles. There is 2.5° polar zoning around the capsule, 60 radial zones in the DT (for ignition capsules), 220 radial zones in the ablator, and 70 radial zones in the hohlraum wall. In the wall zones STA tabular (LTE) wall opacities are used when the zone temperature is less than 300 eV. For wall zone temperatures greater than or equal to 300 eV the DCA model is used for NLTE opacity and equation of state. We use flux limited thermal transport with a limiter of 0.15.

When this model is applied to CH ablator implosions with ~15 ns ("high foot") or ~20 ns ("low foot") laser pulses and helium hohlraum fill densities ranging from 0.96 to 1.6 mg/cc it typically predicts about 30% too much radiation flux compared to the "measured" flux, which is usually inferred by matching the capsule bang time [3]. Experiments using open-ended "viewfactor" hohlraums confirmed that the discrepancy in bang time was primarily due to over-estimating the radiation flux compared to that measured through the open end [4].

2. Experimental results for 2-shock and 3-shock HDC ablator implosions

2.1. Results for hohlraum gas fill densities up to 0.6 mg/cc He

In contrast to the results for CH ablator implosions, when the model described above is applied to HDC ablator implosions with hohlraum gas fills up to 0.6 mg/cc it has been able to predict the total radiation flux measured by the Dante x-ray diode array to within the measurement errors, and has required about a 10% reduction in the absorbed peak power in calculations to match the observed bang times. The HDC radiation drives are shorter than those for CH capsules due to the higher density of the HDC. These experiments also have had low (< 3%) amounts of backscatter [5]. Figure 1 shows a comparison of the measured and calculated Dante flux out of the open end of a gold viewfactor vacuum (no gas fill) hohlraum (NIF experiment N150120-003-999). This experiment was done in a 5.75 mm diameter hohlraum, but with a 3-shock pulse shape that was scaled down by a factor of 0.8. That is, the scaled experiment is designed to produce the same radiation drive that the full-scale pulse would produce in a 6.72 mm diameter hohlraum. We see that the total calculated radiant intensity in GW/sr is within the experimental error bars, as is the gold "M-band" component, which is the radiant intensity for photon energies greater than 1.8 keV. Figure 2 shows similar agreement for a full-scale 6.72 hohlraum with a 0.6 mg/cc helium gas fill (NIF experiment N140701-002-999).

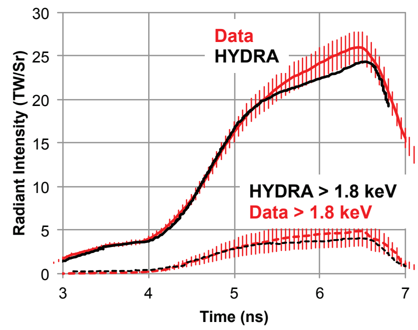

Figure 1. Measured and calculated Dante radiant intensity from the open end of a 5.75 mm diameter vacuum gold viewfactor hohlraum.

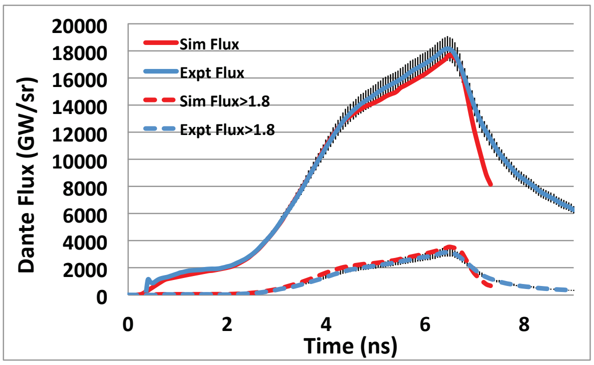

Figure 2. Measured and calculated Dante radiant intensity from the LEH of a 6.72 mm diameter gold hohlraum with 0.6 mg/cc He fill.

2.2. Hohlraum gas fill density scan experiments

While the agreement with our standard model is good for the two cases shown above, it is not a good drive predictor for all HDC ablator experiments. A number of HDC experiments were done with a 3-shock laser pulse, $\Delta\lambda$=0 A, and a hohlraum He fill density of 1.6 mg/cc (e.g. shot N140722-001-999). These were done in 5.75 mm diameter hohlraums with full-scale HDC capsules. This experiment series was more directly comparable to the CH ablator "high foot" series, which had the same hohlraum gas density (1.6 mg/cc). The relationship between measured and calculated drive was similar to what was observed for the CH ablator experiments. They had ~15% backscatter losses and required a further reduction of ~30% in absorbed power in the calculations to match bang time.

To investigate the drive discrepancy more systematically, we undertook a series of experiments in which we varied the hohlraum gas fill density only. These experiments were done in a 5.75 mm diameter hohlraum driven by a 2-shock laser pulse. The capsules were HDC shells filled with a mixture of 70% (atomic) D and 30% ^{3}He. The drive was measured using the Dante x-ray diode and also inferred from the bang time. Figure 3 is a plot of the multiplier applied to the peak of the laser pulse in the calculation in order to match the measured bang time. We see that for fill density less than or equal to 0.85 mg/cc, the required peak drive multiplier is > 0.9. For the two highest fill densities the required multiplier is significantly lower. Since the bang time is measured to about 50 ps accuracy, which corresponds to about 1% variation in the peak flux, the observed drive deviation from the model is well outside of the experimental error.

We also measured and calculated the shape of the imploded capsule at the time of peak x-ray brightness. The calculations have backscatter removed and include the calculated CBET without any ad hoc adjustments. The amount of calculated instantaneous power transfer is generally < 10%, and the total energy transfer is < 3%. Figure 4 shows that in the calculations the P2/P0 Legendre moment of the shape is expected to tend toward a more sausage shape as the gas fill is increased, whereas the data shows the opposite trend.

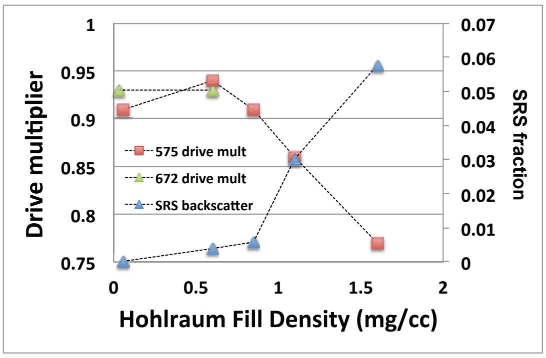

Figure 3. Peak drive multiplier required to make calculation match measured bang time (left) and SRS fraction (right) as a function of hohlraum fill density.

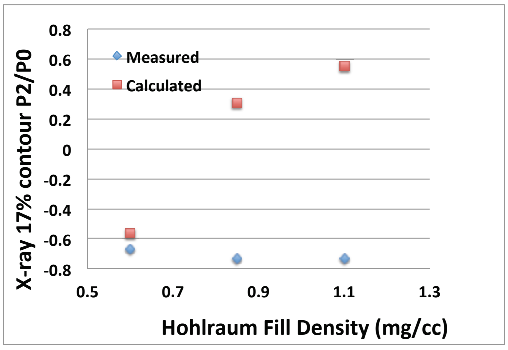

Figure 4. Measured and calculated x-ray P2/P0 as a function of hohlraum fill density.

3. Exploring potential avenues for improving hohlraum modelling capability

In this section we investigate some possible changes in the model that could lead to improved agreement at higher gas fill densities.

3.1. Sensitivity to DCA NLTE transition temperature

In the current model the wall zones transition at 300 eV from using tabular LTE opacities and tabular equations of state to using the DCA NLTE model for both. The reason for this choice is that at the peak of the ~300 eV radiation drive, the wall zones that are heated by x-rays should be in LTE and tabular LTE opacities should be more accurate than LTE opacities calculated using a simpler DCA having fewer transition levels. Wall zones that are above 300 eV are presumed to be heated directly by the laser and thus are probably in NLTE. This model has two problems. First, the transition from the tables to the DCA model is abrupt and leads to sudden jumps in opacity for small changes in temperature. Second, because it does not use a physical basis to decide if a zone is LTE or not, there can often be zones that are using LTE tables when in fact the conditions would drive it into NLTE, and vice versa. Figure 5 shows that the radiation temperature is sensitive to the choice of table transition temperature. For the 1D calculation of a near vacuum hohlraum that is shown, the radiation temperature is almost 10 eV cooler when we transition to DCA at 200 eV instead of 300 eV. This change is mostly due to fact that the DCA model LTE gold opacities are much lower than those from high-resolution tables. Thus, it would be beneficial to move towards a wall model that does not rely on an arbitrary temperature condition to decide when to transition between LTE and NLTE. And it would also help to have a more accurate DCA model that has opacities close to the tabular values when in LTE.

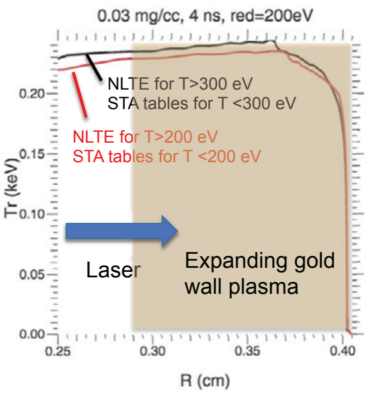

Figure 5. Radiation temperature spatial profile for two different LTE/NLTE transition temperatures.

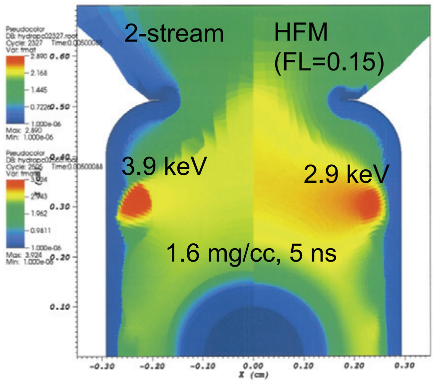

Figure 6. Plot of electron temperature for the 1.6 mg/cc fill shot with 2-stream limiter (left) and flux limiter = 0.15 (right).

3.2. Methods for inhibiting thermal transport to x-ray conversion layer

One hypothesis is that as the hohlraum gas fill is raised, other physics processes not currently included in the model are causing an inhibited heat transport from the coronal plasma to the wall, leading to reduced x-ray drive. One mechanism that has been proposed is the two-stream plasma instability [6]. If this instability is excited, it can quickly grow and saturate, leading to ion acoustic turbulence, which can lead to increased scattering and inhibited thermal transport [7]. In Hydra the two-stream instability is applied as a collision-dependent flux limiter, where the enhanced two-stream collisionality depends on the value of ZT_e/T_i in each zone. When this model is applied to the 1.6 mg/cc He fill case (see figure 3), figure 6 shows that the electron temperature in the coronal plasma heated by the outer beams is ~ 1 keV hotter than when the usual flux limiter of 0.15 is used. The higher temperature leads to a lower radiation drive.

4. Summary

We have described a Hydra model for laser-heated hohlraums that can predict the amount of radiation drive produced in hohlraums with gas fill densities between 0 and 0.6 mg/cc of helium for 2-shock and 3-shock pulses driving HDC ablator capsules. To match the measured bang time, 7-10% of the measured absorbed laser power must be removed from the peak of the pulse in the calculation. A series of 2-shock HDC implosions in which the hohlraum fill density was varied showed that the bang time discrepancy becomes larger for gas fill densities above 0.85 mg/cc. The discrepancy correlates with the amount of measured SRS backscatter. This model does not capture the variation in radiation drive symmetry as a function of the hohlraum fill density. We are currently investigating several different possible improvements to our model to improve its predictability over a broader range of conditions. The improvements include improved wall NLTE models and models that inhibit the thermal transport from the coronal plasma to the x-ray conversion layer. This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

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