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## Observation of high soft x-ray drive in large-scale hohlraums at the National Ignition Facility

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The first soft x-ray radiation flux measurements from hohlraums using both a 96 and a 192 beam configuration at the National Ignition Facility have shown high x-ray conversion efficiencies of 85-90%. These experiments employed gold vacuum hohlraums, 6.4 mm long and 3.55 mm in diameter, heated with laser energies between 150 - 635 kJ. The hohlraums reached radiation temperatures of up to 340 eV. These hohlraums for the first time reached coronal plasma conditions sufficient for two electron processes and coronal heat conduction to be important in that determining the radiation drive.

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High energy density laser experiments use hohlraums made of high-Z materials to convert laser energy into soft x-rays with an approximately Planckian radiation spectrum. The hohlraum x-ray radiation is used to drive a wide range of physics experiments to study equations of state/material dynamics [1], hydrodynamic instabilities [2, 3], radiation transport [4, 5], and astrophysical processes [6]. The advantage of converting the laser to x-rays lies in the fact that hohlraum x-ray sources provide a uniform illumination for physics experiments, eliminating laser imprint due to spatial variations in the intensity of the impinging laser light. The penalties in converting the optical laser light to x-ray radiation include losses in heating the hohlraum wall and incomplete conversion of the laser light to x-rays. The completion of the National Ignition Facility (NIF) [7] opens new possibilities to scale experiments to larger sizes and to higher radiation fluxes[8] allowing exploration of new physics regimes.

The conversion of laser light to x-rays in a hohlraum is described by the following power balance equation:

$$P_{\text{rad}} = \eta(P_l - P_{\text{backscatter}}) = \sigma T_{\text{rad}}^4 (A_w(1 - \alpha) + A_h), \quad (1)$$

where  $P_{\text{rad}}$  is the total x-ray production,  $\eta$  is the x-ray conversion efficiency of the laser power to soft x-rays,  $P_l$  is the laser power,  $P_{\text{backscatter}}$  is the backscattered laser power not coupled to the hohlraum,  $\sigma$  is Boltzmann's constant,  $T_{\text{rad}}$  is an effective temperature characterizing the total x-ray flux,  $A_w$  is the area of the hohlraum wall,  $A_h$  is the area of the laser entrance holes, and  $\alpha$  is the wall albedo defined as the ratio of the emitted x-ray flux from the hohlraum wall to that incident on the wall. For experiments, the incident laser power, the radiated power escaping through the laser entrance holes, and the backscattered laser power are measured, leaving the conversion efficiency and wall albedo to be inferred using the above equation. The conversion efficiency describes the fraction of absorbed laser power that is converted into soft x-ray flux.

Absorbed laser power not converted into x-rays is retained in the hot, under-dense coronal plasma such that  $P_{\text{rad}}=P_{\text{l}}-P_{\text{backscatter}}-P_{\text{corona}}$  where  $P_{\text{corona}}=(1-\eta)(P_{\text{l}}-P_{\text{backscatter}})$ . It should also be noted that the addition of an experimental physics package or a capsule in the hohlraum contributes an additional loss term reducing the radiation temperature.

As hohlraums increase in size with the available energy on the NIF, the volume of the coronal plasma increases more rapidly than the wall area. NIF scale hohlraums have ~8 times (or more) the wall area and ~20 times the volume of Nova/Omega scale hohlraums. Consequently, the fraction of total energy retained in the corona versus the fraction absorbed in the walls is significantly greater on NIF than on Nova or Omega; ~15-30% on NIF versus 5-10% on Nova. Because of this, predictions of NIF hohlraum radiation temperatures are more sensitive to models that change the coronal energy than previous Nova/Omega hohlraums [9]. Two important processes affecting  $P_{\text{corona}}$  are plasma emissivity and electron heat conduction. There are several physics models for both of these in the radiation hydrodynamics codes used to simulate hohlraum targets. Discrepancies in the simulations with different models of emissivity and electron heat conduction which could not be differentiated by smaller hohlraums now become apparent as demonstrated by comparisons of the simulations with the data from the experiments presented here.

In this letter, we report on the first high-energy density large-scale vacuum hohlraum experiments showing x-ray radiation fluxes 20-30% higher than anticipated using conservative models benchmarked by smaller hohlraum targets on Nova and Omega.[10-13] We find that simulations using less conservative atomic physics and electron heat transport models agree with the measurements and indicate a hohlraum x-ray conversion efficiency of approximately 90%.

In this study, the hohlraums were heated with NIF's 192 laser beams of 351 nm laser light. The beams are arranged into four beam cones for both the lower and upper hemispheres of the spherical target chamber. The two inner beam cones are at 23.5° and 30° with respect to the vertical axis while the outer beam cones are at 44.5° and 50° (Figure 1). There are twice as many beams in the outer beam cones as in the inner cones so that approximately two thirds of the total available laser energy is contained in the outer beams. The total laser energy and power delivered by each quad is measured with  $\pm 2\%$  and  $\pm 3\%$  accuracy, respectively. The experiments were performed with both a 96- and a 192-beam configuration with energies ranging from 150 – 635 kJ at 351 nm in 2 ns square pulses. For the 96-beam configuration, only the beams at 30° and 50° were used. The beams were smoothed using polarization smoothing, 45 GHz Smoothing by Spectral Dispersion (SSD), and Continuum Phase Plates (CPPs) [14, 15]. The CPPs in each cone produced a different elliptical spot size at best focus giving intensity ranges of  $\sim 1.8\text{-}4.0 \times 10^{14}$  W/cm<sup>2</sup> for the 23.5° beams,  $\sim 2.0\text{-}4.5 \times 10^{14}$  W/cm<sup>2</sup> for the 30° beams,  $\sim 4.3\text{-}9.4 \times 10^{14}$  W/cm<sup>2</sup> for the 44.5° beams, and  $\sim 4.9\text{-}10.8 \times 10^{14}$  W/cm<sup>2</sup> for the 50° beams. Backscatter diagnostics were fielded on the high energy shots for a single quad of beams in both the 30° and 50° beam cones. We find that the total reflected energy due to laser backscatter instabilities is less than 2% of the total incident energy. In addition, a static x-ray imager consisting of a four pinhole x-ray camera, was employed to measure the focal spot locations of the beams irradiating the inside of the hohlraum [16].

The gold vacuum hohlraum targets were used have a wall thickness of 25 microns, a length of 6.4 mm, an inner diameter of 3.55 mm and a laser entrance hole diameter of 2.65 mm (Figure 1). The hohlraums were aligned along the vertical axis of the target chamber. The soft x-ray radiation drive was measured using the Dante diagnostic [17]. Dante is an 18 channel,

absolutely calibrated, broadband soft x-ray spectrometer, which uses signals filtered by combinations of x-ray edge filters, mirrors, and diodes to determine the flux in different spectral regions [18]. A spectral unfold algorithm uses the measured fluxes in each channel to reconstruct the spectrum of the radiation exiting the hohlraum laser entrance hole. An example of the spectral reconstruction is included in Figure 1. We use the integrated flux up to 13 keV as a measure of the total flux.

Figure 1 shows the calculated specific energy in the coronal plasma for two radiation hydrodynamic simulations using different models. The calculations of the specific energy in the coronal plasma on the top half of the image uses the conservative radiation-hydrodynamic modeling that agreed well with Nova/Omega data. It employs the Nonlocal Thermodynamic Equilibrium (NLTE) XSN average-atom atomic physics model [19] and an electron heat transport flux limiter of 0.05. The XSN average-atom atomic physics model tracks the shell populations of the principle quantum levels averaged over all ionic states and in its default mode does not include two electron processes, i.e. dielectronic recombination. Shown on the bottom half of the image is a calculation that uses a NLTE Detailed Configuration Accounting (DCA) atomic physics model accounting for two-electron processes with a flux limiter of 0.15. Unlike the XSN model, the DCA model solves rate equations for populations of the most dominant excited states for all ionization states. Recent improvements to the DCA model [20] have increased computing efficiency so that it can be routinely used in integrated simulations. Both calculations use a flux-limited heat diffusion model that chooses on a per zone basis in the simulation the minimum of either the Spitzer-Harm electron heat flux,  $k_{SH} \nabla T_e$  where  $k_{SH}$  is the Spitzer-Harm conductivity and  $T_e$  is the electron temperature or a fraction of the free streaming heat flux,  $f v_e n_e T_e$ , where  $f$  is the flux limiter value,  $v_e$  is the electron thermal velocity, and  $n_e$  is the

electron density. The value of the flux limiter affects the flow of energy carried by the electrons. It is clear that the specific energy in the coronal plasma is higher in flux-limited XSN than with the DCA model.

The time history of the measured x-ray radiation flux for a hohlraum with 635 kJ of energy is shown Figure 2. The measured flux is compared with simulations that use flux-limited XSN and DCA models with flux limits of 0.05, 0.15, and 1.0 where the flux limit of 1.0 is the free streaming limit. Applying a DCA versus a XSN model with the prior standard flux limit of 0.05 only accounts for about 1/2 of the increase in the measured flux. The DCA model with a flux limit of 0.15 is in best agreement with the experimental results at the peak of the laser pulse. At the same time, there is little difference between the flux limit values of 0.15 and 1.0 indicating that the coronal plasma in the simulation is cold enough that the heat transport is Spitzer-like and not largely affected by the flux limiter. The peak fluxes for both of these simulations, as well as the measurements, are ~20-30% larger than the peak radiation fluxes predicted by the XSN models regardless of the flux limit. This illustrates that both changes in the atomic physics model and heat conduction are necessary to bring the simulations in agreement with the peak x-ray flux measurements. Additional comparisons with simulations including variations of atomic physics model parameters, changes in atomic physics multipliers, and changes in the flux limiter showed that neither changes in the flux limiter nor the atomic physics modeling alone could match the levels of peak radiation flux observed in the experiments. Applying the flux-limited DCA model with a flux limit of 0.15 to all of the 0.7-scale hohlraum experiments shows good agreement with the experimental measurements (Figure 3).

The agreement between the measurements and the simulations using the flux-limited DCA atomic physics model with the flux limit of 0.15 is an indication that higher coronal plasma

emissivities lead to cooler plasmas absorbing less specific energy and allowing more x-rays to heat the wall. Higher hohlraum wall temperatures lead to an increased thermal x-rays flux. The change in the flux limiter value has a similar effect with respect to electron heat transport. Increasing the flux limit allows more of the laser energy absorbed by the corona to flow to the wall through electron heat conduction. Both changes lead to an increase in the x-ray conversion efficiency resulting in a factor of two less specific energy being absorbed by the coronal plasma as shown by the comparison of the DCA atomic physics model with a flux limit of 0.15 and the XSN atomic physics model with a flux limit of 0.05 in Figure 1.

Past experimental measurements of the plasma conditions in laser produced foil plasmas using Thomson scattering have also shown the discrepancy between the DCA and XSN models. In those experiments, the DCA model was a better fit to the measurements [21, 22]. Those experimental measurements also show the deficiency with the flux limited diffusion model. Since the flux-limiter is typically fixed during the entire simulation, the model cannot account for changing plasma conditions in the hohlraum that would affect the heat conduction, while a non-local heat conduction model may provide better agreement over the duration of the experiment [23, 24]. Other recent experiments to measure the x-ray conversion efficiency using spherical gold targets have also required an increase in the flux limit from 0.05 to 0.15 in order to get agreement between the simulations and the experimental measurements [25].

The experimental results presented here show that vacuum hohlraums continue to “work” at energy levels some 10-20 times greater than previously used (while keeping the energy density approximately fixed). The laser energy scaling of the peak radiation fluxes and temperatures is summarized in Figure 4. They also show the increased importance, as we increase scale size, of the energy stored in the corona that fills the hohlraum and the need to more accurately model

NLTE emissivity and electron heat transport. We also demonstrated a peak x-ray radiation temperature on NIF of 340 eV, that could only be achieved previously with very small hohlraums [26]. The increase in hohlraum size at constant radiation drive enables significantly larger scale x-ray driven physics applications. This, in turn, enables a wide variety of physics applications that can take advantage of larger scale sizes to discern physical features and drive experiments to higher ablation pressures. For example, at these radiation temperatures, ablative pressure drive scales as  $P(\text{Mb})=3 \times 10^{-7} T_{\text{rad}}(\text{eV})^{3.5}$  [27] for CH material, with a higher coefficient for Beryllium[28]. This leads to pressures on the order of ~220 Mbar as opposed to Nova/Omega hohlraums which, besides reaching half the ablative pressure for practical applications, had 5x smaller linear dimensions for experimental physics packages.

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## Captions

**Figure 1:** Plot shows the experimental configuration of the targets including the four beam cones and dimensions of the scale 0.7 hohlraums. Included in the figure is a calculation of the specific energy stored in the coronal plasma for the flux-limited XSN (top) model with a flux limit of 0.05 and DCA (bottom) models with a flux limit of 0.15 at 2 ns in the laser pulse for 635 kJ. The spectrum at peak x-ray flux is included as measured by (—) Dante and overlaid with the (—) calculated spectrum using the DCA model and a flux limit of 0.15.

**Figure 2:** (●) Experimental measurements compared with radiation hydrodynamic simulations of vacuum hohlraums on the NIF with the XSN atomic physics model with a flux limiter of (---) 0.05, (---) 0.15, and (---) 1.0 along with calculations using a DCA model with a flux limiter of (—) 0.05, (—) 0.15, and (—) 1.0.

**Figure 3:** Comparison of the time histories of the measured flux with simulations using the DCA model with a flux limiter of 0.15 for increasing laser energies of (▲) 150, (◆) 233, (●) 308, and (■) 635 kJs.

**Figure 4:** Scaling of the (●) measured peak radiation fluxes compared with that of flux-limited XSN simulation with a flux limit of (---) 0.05 and of the DCA model with a flux limit of (—) 0.15. The peak radiation temperatures (■) measured are also plotted.







