High Temperatures in Inertial Confinement Fusion Radiation Cavities Heated with 0.35 μm Light

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(Received 23 May 1994)

We have demonstrated efficient coupling of 0.35 μm laser light for radiation production in inertial confinement fusion (ICF) cavity targets. Temperatures of 270 eV are measured in cavities used for implosions and 300 eV in smaller cavities, significantly extending the temperature range attained in the laboratory to those required for high-gain indirect drive ICF. High-contrast, shaped drive pulses required for implosion experiments have also been demonstrated for the first time. Low levels of scattered light and fast electrons are observed, indicating that plasma instability production is not significant.

PACS numbers: 52.50.Jm, 52.40.Nk, 52.70.La

Inertial confinement fusion (ICF) uses high powered laser or particle beams to compress and heat capsules containing fusion fuel with the goal of producing thermonuclear energy [1,2]. One proposed method for ICF is x-ray drive where high powered beams heat high-Z cavities, or *Hohlraums*, converting the driver energy to x rays which implode the capsule [3]. Present indirect drive target designs predict ignition, and gain can be attained with a 1–2 MJ laser for radiation drive temperatures on the order of 300 eV [4]. In this Letter we report experiments using the Nova laser that demonstrate efficient cavity heating with 0.35 μm light to the temperatures required for these ignition target designs. Radiation temperatures in excess of 270 eV have been obtained in cavities used for implosions [5], while 300 eV temperatures have been obtained in smaller cavities. These radiation cavities are the highest thermal sources measured in the laboratory. The temperature scaling is consistent with a simple power balance model successfully used to model previous experiments at lower temperatures [6,7], extending its proven range of validity. We have demonstrated that shaped radiation drive pulses required to control shock preheat can easily be attained by varying the incident laser power. Laser-plasma instabilities [8] that could reduce coupling efficiency and produce superthermal electrons appear not to be significant. Fast electrons are low, typically less than a few percent, indicating superthermal electron preheat is small. In addition to high density implosion experiments [9,10], these cavities have been used for a variety of radiation heating experiments including hydrodynamic instability studies of radiatively accelerated material both in planar [11,12] and convergent systems [13] and opacity experiments of radiatively heated material [14].

Radiation cavities are nearly completely enclosed structures of high-Z material. Laser beams are focused through small holes in the cavity onto its wall, where their energy is partially converted to x rays. The high-Z walls are heated by a thermal diffusion wave, driven by absorbing and reemitting x rays, which propagates into the cold wall material [15]. In addition, energy can be lost by radiation through holes in the cavity or be absorbed by low-Z material such as ICF capsules placed in the cavity. Models [7,16] have been developed for radiation heating of high-Z material that balances the incident flux from a heating source S_s and reradiating sources from the other walls S_i with the absorbed flux S_a and reradiated flux S_r from the wall element, or

$$S_c = S_s + S_i = S_a + S_r . \tag{1}$$

S_c is the total flux on the wall element. Equivalently, the power balance for the entire cavity can be formulated assuming uniform temperature as

$$\eta P_L = A_t[(1 - f)S_a + fS_c], \tag{2}$$

where $\eta P_L = A_t S_s$ is the total heating source from the laser, which is assumed to be proportional to the incident laser power P_L. The constant η is the fraction of laser light useful for heating the cavity. f is the fraction of the total cavity surface area A_t that is holes (or absorbing material). This power balance is intuitive since it equates the source, or heating flux, on the left-hand side of Eq. (2) with the sum of the power absorbed by the wall and the power escaping from holes in the cavity, or into absorbing material.

Experiments have been performed using the Nova laser [17] to measure drive scaling and laser coupling in cavity targets used for implosions and other radiation heating experiments. Targets are right circular cylinders of high-Z material, typically Au. Ten Nova beams, five per side, are focused through laser entrance holes (LEH) in the ends of the cylinders onto the cylinder walls, as shown schematically in Fig. 1. The geometry is chosen to minimize asymmetries for implosion experiments [4]. Cavities are heated with as much as 30 TW of 0.35 μm light in a 1 ns square laser pulse or with shaped pulses as long as 3.7 ns with up to 40 kJ of laser energy. The

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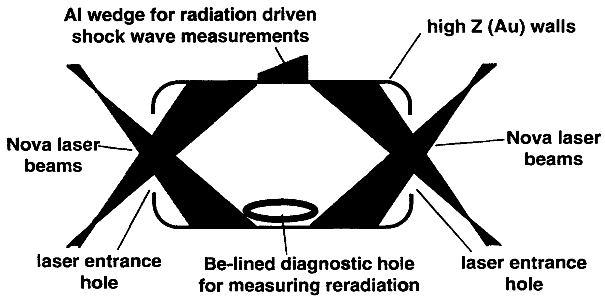

FIG. 1. The Nova laser heats radiation cavities that are right circular cylinders by focusing the beams through laser entrance holes onto the high-Z cavity wall. Radiation production is measured in the center of the cavity using two complementary techniques.

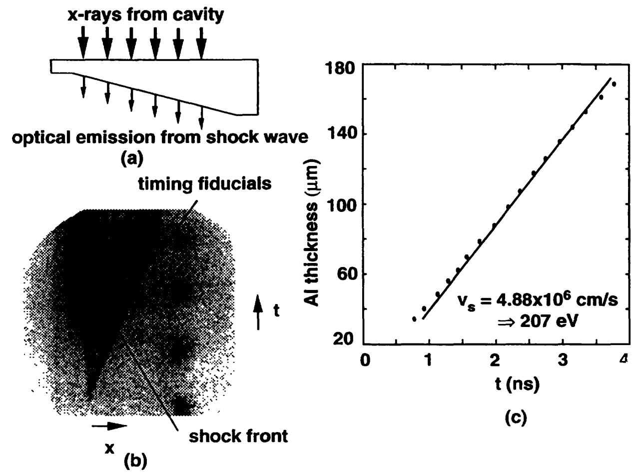

FIG. 2. Radiation production in the cavity is measured from the shock wave produced in Al. (a) X rays produce a shock wave in a continuously (or discretely) varied thickness of Al placed on the cavity wall. (b) The time history of the optical signal from the emerging shock is shown as recorded on an optical streak camera. (c) The slope of the beginning of the optical emission can be used to derive a shock velocity from which a radiation drive temperature can be derived.

nominal size of the cavity is 1.6 mm diameter, 2.5–2.8 mm long, and the wall thickness is typically ~25 μm. The size of the LEH varies from 50% to 75% of the cavity diameter. The beams normally cross at the center of the LEH with the best focus placed 1 mm from the crossing point outside the cavity. Average intensity on the cavity wall is $\sim 1 \times 10^{15}$ W/cm^2 for 30 TW pulses. Scaling is investigated using 1.2 mm and 1.0 mm diameter targets whose other dimensions are scaled appropriately.

The radiation temperature T_R in the cavities is determined using two independent methods. One method measures T_R by observing the velocity of a shock wave generated when radiation is absorbed in low-Z material, typically Al. T_R can be correlated to the shock velocity u_s using strong shock relations [18]. For low-Z materials, the hot ablated plasma is relatively transparent to the x rays, while the cold material is very absorptive, establishing a sharp heat front. The heat front is subsonic and establishes a shock wave ahead of it. The shock velocity scales approximately as $u_s \propto T_R^{7/4}$ with the proportionality constant depending on the equation of state. A slight correction to the temperature scaling is needed for the reradiation of Al. For the temperature range of these experiments the scaling is $T_R = 0.0126 u_s^{0.63}$, where T_R is in units of eV and u_s is in units of cm/s.

The shock velocity is measured by placing an Al plate over a hole in the cavity. Its thickness is continuously varied, as shown schematically in Fig. 2(a), or varied in discrete steps. Optical emission is produced when the radiation generated shock wave emerges from the rear surface. The optical emission is imaged onto the slit of an optical streak camera using an $f/10$ Cassegrain telescope. An example of data is shown in Fig. 2(b) for laser heating pulse 2.2 ns long with a 3:1 contrast. The onset of optical emission as a function of time is extracted and correlated with the initial Al thickness as shown in Fig. 2(c). Estimated error for measuring drive is ±5 eV, which includes the accuracy of the measurement and the uncertainty in the shock scaling.

The other method measures the reradiated flux S_r from the x-ray heated wall similar to previous cavity characterization experiments [6,7]. The flux is measured using an array of x-ray diodes [19] through a Be-lined hole in the *Hohlraum* wall placed so that the diodes view only unirradiated wall. Time resolution is on the order of 150 ps limited by the bandwidth of the detectors and oscilloscopes and correlation of the timing among the detectors. Spectrally integrated flux is measured to an accuracy of ~25% including calibration errors and unfolding uncertainties resulting in ±6% when converted to an equivalent radiation temperature using the Stefan-Boltzmann law.

The two drive characterization methods sample different but related quantities. The shock wave method directly measures the cavity flux incident S_c while the reradiated flux method measures S_r. The two measurements are related by the wall reflectivity, S_r/S_c. The flux of interest for ICF and other applications is S_c, which makes the shock velocity method more relevant, but it provides limited time resolution and no spectral information. The reradiated flux measurement has much better time resolution, important for studying shaped drive, and provides some information on the drive spectrum.

Scaling experiments have been performed using 1 ns constant power (square) laser pulses. Scaling of T_R as a function of average laser power is shown in Fig. 3 for 1.6 mm diameter cavities as measured from the shock breakout. Most data are from targets 2.55 mm long, although some data from longer targets are included. Small corrections (< 5 eV) have been made to these

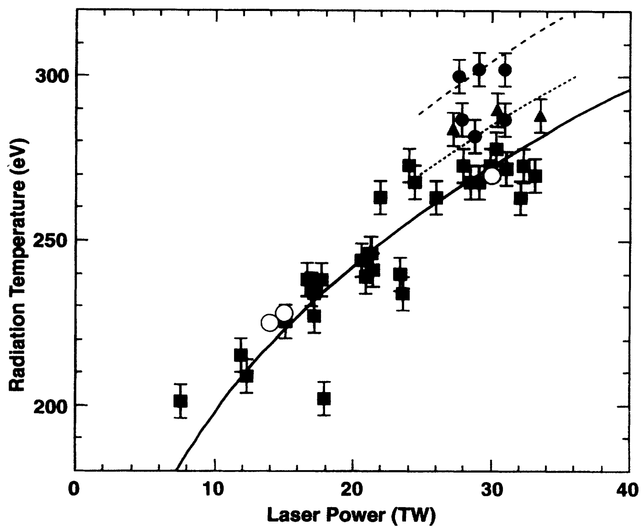

FIG. 3. Drive scaling as a function of incident laser power for 1 ns laser pulses. The experimental results for the 1.0 mm, 1.2 mm, and 1.6 mm diameter cavities are shown by the closed circles (●), triangles (▲), and squares (■), respectively. The open circles (○) are results of 2D LASNEX calculation for the 1.6 mm cavity. The lines (- -1.0 mm, ··· 1.2 mm, —1.6 mm) are fit to the data using Eq. (2) and wall loss scaling from Sigel *et al.* [7].

data for comparison. T_R is around 270 eV for 30 TW of incident laser power. In limited experiments with smaller cylindrical cavities, we measure temperatures of 290 and 300 eV for a 1.2 and 1.0 mm diameter cavity, respectively. These data are also shown in Fig. 3. For the 1.0 mm diameter cavity, the laser entrance holes were larger so that the fraction of hole area is increased to 11% vs 6% for the larger targets. Previous experiments have reported temperatures of 240 eV using 1 mm diameter spherical cavities heated with 5.5 TW of 0.35 μm light using the GEKKO laser at Osaka [6]. The present experiments significantly extend the range of radiation temperatures attained in the laboratory to temperatures of interest for high-gain implosions.

The data in Fig. 3 can be fitted by Eq. (2) using the radiation heating model of high Z walls by Sigel *et al.* [7] with the fitting parameter η. Results of the fit are the lines shown in Fig. 3 with η being 0.75, 0.65, and 0.50 for the 1.6 mm, 1.2 mm, and 1.0 mm diameter cavities, respectively. Standard deviations of the fits are ± 0.1, consistent with measurement accuracy for laser power and T_R. The fit for the 1.6 mm cavities follows the trend of the data quite well, demonstrating the scaling with the simple power balance model. Present high-gain target designs use cavities whose dimensions are approximately 3.5 times the 1.6 mm diameter cavity. The laser pulse has a complex shape that is approximately 20 ns long with a 3 ns high power portion at the end. Peak irradiance on the wall for the high-gain target is also similar to that for the 1.6 mm diameter target. Using Eq. (2) to extrapolate to these conditions, the peak laser power required is estimated to be ~400 TW, or 1.2 MJ for an η of 0.75. This laser power estimate is consistent with more detailed calculations of high-gain target design.

The 1.6 mm cavities have been modeled using 2D LASNEX, a radiation hydrodynamics simulation code including treatment of the laser rays and energy deposition [20]. Results of the calculations are also shown as open circles in Fig. 3. In general, the modeling results agree with the experiment, indicating that the calculations are predicting laser deposition x-ray conversion, x-ray absorption by the wall, and reradiation correctly. The agreement also supports predictions for extrapolation to high-gain targets which use the same modeling.

For high-gain implosions the driving pulse is ramped to reduce shock preheating of the fuel before compression [1,2]. We have generated a number of high-contrast, shaped radiation pulses on Nova for a variety of experiments simply by varying the temporal profile of the incident laser pulse. Previous experiments have reported results using only simple quasi-Gaussian laser pulses. An example of a shaped radiation pulse measured is shown in Fig. 4 along with the incident laser power. The incident laser pulse is 2.2 ns long with a 3:1 contrast ratio from the start of the pulse to its peak. The resulting reradiated brightness temperature, $(S_r/\sigma)^{1/4}$, is 135 eV in the initial part of the pulse with a peak of 200 eV, or a flux (σT_R^4) contrast of ~4. Other tailored pulses have been successfully demonstrated on Nova with pulses as long as 3.7 ns. As the pulse length increases, energy limits on Nova restrict the peak temperatures available. The ease of obtaining shaped laser pulses allows a significant flexibility in optimizing implosion experiments.

Consistency between the two methods for drive measurements is important to demonstrate understanding of the cavity radiation environment and radiation heating of

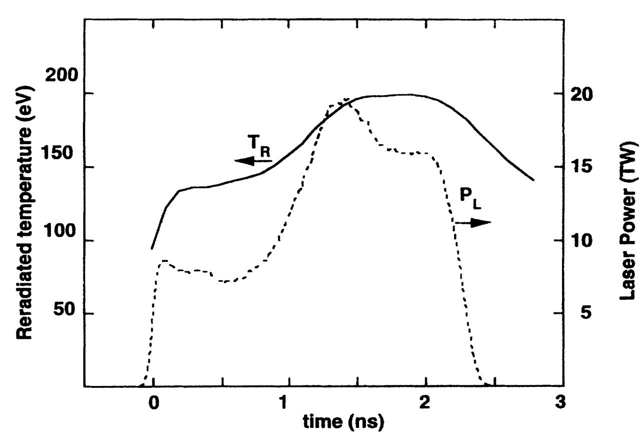

FIG. 4. Example of shaped radiation drive pulse (—) compared with the incident laser pulse (- -). The laser pulse is the sum of the ten incident laser beams.

high Z materials. Data in Figs. 2 and 4 are from the same experiment. The measured wall reflectivity, S_r/S_c, at peak drive for this experiment is 0.87 agreeing with a value of 0.84 calculated using the scaling by Sigel *et al.* [7]. Similar comparisons have been done for many of the 1 ns experiments, and these also show similar agreement supporting present models of radiation heating and cavity temperature scaling.

In addition to providing high drive, cavities heated with 0.35 μm light produce low levels of plasma instabilities. Absorption is measured by collecting light scattered back through the lens into a calorimeter and obliquely scattered using an array of photodiodes distributed around the chamber. Absorption is greater than 90%, nearing the limits of the measurement technique, even for the smallest targets discussed here. Fast electron levels, inferred from bremsstrahlung x rays from the cavity walls, are on the order of 1% for the 1.6 mm diameter targets and less than 2% (3%) for the 1.2 mm (1 mm) diameter targets in a 50 keV superthermal distribution. For the shaped pulses fast electron levels are 0.3% or less. Scattered light levels from the Raman instability show a scaling similar to the fast electron measurements. The fast electron production correlates well with levels measured in disk experiments at similar irradiances. This is consistent with estimates of collisional damping thresholds for Raman production [21]. The fast electron levels are estimated to produce negligible preheat for capsules if they were present. Assuming the fast electrons irradiate all of the surfaces uniformly, the preheat on the inner pusher layer is estimated to be less than 1 eV for 1% fast electron levels for both typical Nova experiments [5,10] and high-gain target designs. More detailed estimates of preheat must include electron angular distribution geometry effects of the implosion and detailed calculations of the deposition.

In summary, we have produced high drive, low preheat cavities on Nova using 0.35 μm light that are suitable for implosion and radiation heating experiments. Temperatures of 300 eV have been observed significantly extending the range of cavity temperatures attained in the laboratory to those relevant for high-gain implosions. The drive scaling has been measured as a function of laser power and has been shown to follow a simple power balance model. Detailed calculations also predict the data allowing extrapolation to larger targets with longer pulse lengths similar to those required for high-gain implosions. Pulse shaping of the radiation drive required for high-gain implosions also has been demonstrated for the first time. Fast electrons levels are low with simple estimates indicating that they are not significant sources of preheat.

The authors acknowledge the large number of individuals at our laboratory who contributed to these results that have been acquired over the last several years. We acknowledge the efforts of Nova laser operations and target fabrication who have made the experiments possible and the LASNEX team that made the accurate simulations possible. This work was performed under the auspices of the U.S. DOE by Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48.

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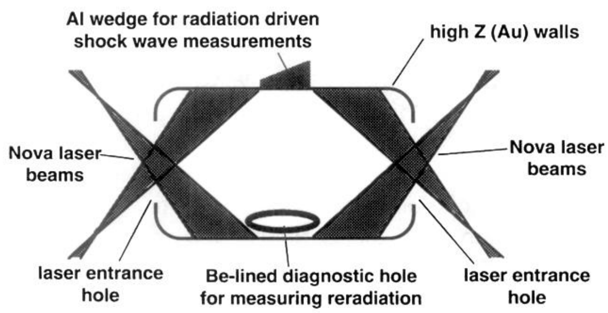

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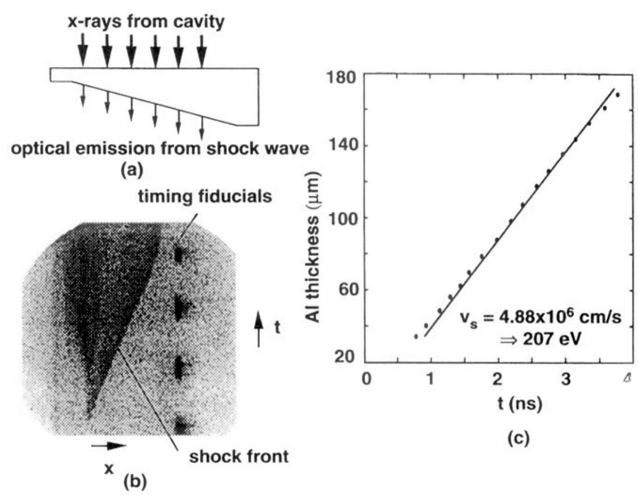

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