SAND99-2190C

Characteristics of ICF Relevant Hohlraums Driven by X-Rays from a Z-Pinch

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ABSTRACT

Radiation environments characteristic of those encountered during the low-temperature *foot pulse* and subsequent higher-temperature *early-step pulses* (without the foot pulse) required for indirect-drive ICF ignition on the National Ignition Facility have been produced in hohlraums driven by x-rays from a z-pinch. These environments provide a platform to better understand the dynamics of full-scale NIF hohlraums, ablator material, and capsules prior to NIF completion. Radiation temperature, plasma fill, and wall motion of these hohlraums are discussed.

I. INTRODUCTION

The dynamics of the proposed He-fill wall tamping and hole closure in the National Ignition Facility (NIF) hohlraum [1, 2], and improved understanding of capsule ablator burn-through rates and shock propagation velocities using NIF-relevant pulse shapes and hohlraum sizes are needed to better design these components [3, 4]. In this paper, we show that hohlraums (Fig. 1) using a static-wall-hohlraum geometry [5] heated by x-rays from a z-pinch on the Z generator [6] are capable of providing radiation fields for such pre-NIF studies. Moreover, such environments offer the opportunity to study the implosion of D_2 filled capsules capable of generating thermonuclear neutrons that would be also useful for NIF-relevant neutron diagnostic development [7] and capsule fabrication performance studies [8].

Figure 1 illustrates the static-wall hohlraum in two geometrical arrangements. In the single-sided x-ray drive of Figure 1A, the hohlraum is placed, on axis, above a pulse-shaping target (PST) within an x-ray-producing z-pinch. In the two-sided x-ray drive of Fig. 1B, the hohlraum is sandwiched between two PSTs. In either case, x-rays produced in the PST enter the axial hohlraum through one or two radiation-entrance-holes (REH) and heat its walls. The x-rays are generated in the PST by the thermalization of the kinetic energy acquired when a cylindrical plasma shell, created by one or more wire arrays, collides with the PST within the z-pinch. In this arrangement, the wires (which are made of tungsten) form an annular plasma radiation case [9] by the time they strike the PST (first strike). The high-atomic-number radiation case traps a fraction of the x-rays produced in the PST (as in a dynamic-hohlraum [10]), and radiation flows from the interior of the PST into the axial hohlraum, whose walls remain relatively static. A low-opacity foam fill is used in some of the PSTs so that as final stagnation is approached, the foam remains transparent to the x-rays, yet provides a back-pressure on the imploding mass. The back-pressure enables additional energy to be extracted from the acceleration and increases the x-ray energy generated as

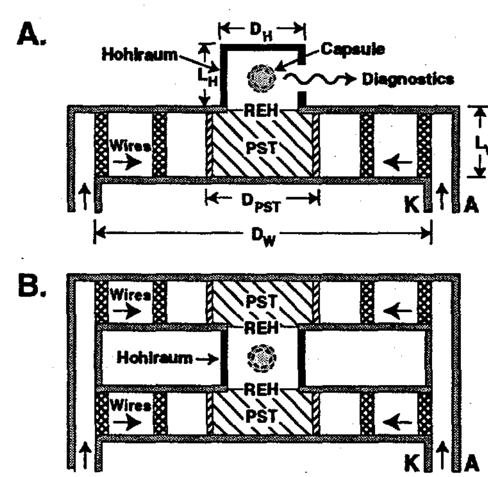

Figure 1: Schmatic of (A) single-sided drive tested on Z, and (B) two-sided drive under development.

the magnetic field compresses the PST. The x-ray pulse and the associated heating of the hohlraum is varied by changing the PST. The single-sided drive of Fig. 1A is that which has been tested to date and is that which is associated with the measurements discussed here. The two-sided drive of Fig. 1B is presently under development. It will permit both hotter and more spatially symmetric radiation fields to be produced within the hohlraum, where a capsule could be positioned with appropriate shine shields.

II. EXPERIMENTAL ARRANGEMENT

The use of large numbers of wires in arrays with interwire spacing <0.5 mm is essential for generating high radiated powers from z-pinches [9, 11]. Nesting the arrays, moreover, enhances the power in targetless pinches [12]. Accordingly, the z-pinch load in these experiments (Figure. 1A) is made of outer and inner arrays of wire where the spacing is ~0.5mm. The associated array diameters (D_W) of 35-40 mm and 17.5-20 mm, array masses of ~2 mg and ~1 mg, and wire length (L_W) of 7-10 mm used are designed to provide reasonable coupling of the generator's magnetic energy into kinetic energy of the arrays prior to stagnation. Optimization of this coupling into x-rays has yet to be completed. The measurements presented here are only a sample of that which can be achieved with this geometry.

The hohlraums used are thin walled (25.4-μm thickness) gold cylinders, measuring either 6-mm in diameter (D_H) by 7-mm in height (H_H) (ignition scale) or 4-mm in both diameter and height. The hohlraums are empty, except that used for shot Z459 (Section III). The hohlraum temperature is measured with two independent diagnostics, each of which views the interior wall of the hohlraum through the same aperture (~3-mm diameter for the 6x7-mm hohlraum or 2-mm diameter for the 4x4-mm hohlraum) [13]. One measurement uses a transmission-grating-spectrometer. The other measurement uses a total-energy bolometer and filtered x-ray diodes. The peak temperature extracted from either set agrees with one another to ±3%.

Plasma closure of the diagnostic hole with time is measured with a multi-filtered, fast-framing, pin-hole camera sensitive to x-rays in four discrete spectral channels covering 100 to 600 eV. For the temperatures discussed here, a correction for the reduced hole size with time based on the these images is used. For the 4x4-mm^2 hohlraum with the smaller diagnostic hole, a 5-mg/cm^2 CH foam is placed in the hole to retard hole closure. Radiation magnetohydrodynamic code (RMHC) calculations show, however, that the CH did not reduce the closure rate and only acted to reduce the measured temperature by ~2 eV. Limited images of the hole were available for this condition. Accordingly, the closure rate measured for the large untamped hole is used to correct the temperature measured for the small hole when images were unavailable.

The radiation entering the hohlraum is estimated by an additional suite of on-axis diagnostics [10] that view the source through the REH when the hohlraum is not present. Over the measured x-ray input powers P of 0.7 to 13 TW, the hohlraum temperature T scales as the Planckian relation $T \sim (P/A)^{1/4}$, where A is the surface area of the hohlraum (Figure 2). In Figure 2, all the data except the highest temperature data of ~150 eV correspond to those measured with the 6x7-mm hohlraum [13].

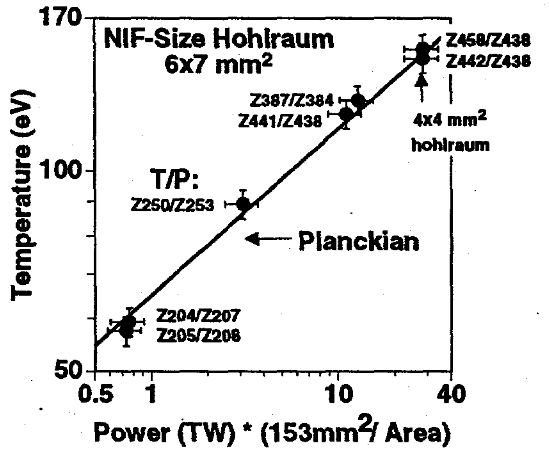

Figure 2: Measured hohlraum temperature (Shot T) as a function of measured on-axis x-ray power (Shot P). The Planckian is normalizied by a calculation at 13 TW [13]. 153 mm^2 corresponds to the surface area of the 6x7-mm^2 hohlraum.

III. TEMPERATURE PROFILES

Figure 3 illustrates two representative temperature profiles designed to ignite 2-mm diameter Be-coated capsules on NIF. In the figure, W and D correspond to the 300-eV peak-temperature and 250-eV reduced peak-temperature drive of References 14 and 15, respectively. Shown also in the figure are three temperature pulse shapes measured with two different PSTs and the two different hohlraum sizes. Shots Z251 (Figure 3A) and Z441 (Figure 3B) use the 6x7-mm^2 hohlraum, while Z459 uses the 4x4-mm hohlraum (Figure 3C). Shot Z251 uses a 5.8-mm diameter REH with a PST of 8 mm diameter (D_{PST}) and a 18-$\mu g/cm^2$ Cu shell filled with 10 mg/cm^3 foam. Shots Z441 and Z459 use a 4-mm diameter REH with a 5-mm diameter PST constructed solely of 14-mg/cm^3 foam. In Z459, the hohlraum is filled with a low-density 10 mg/cm^3 CH foam. Relative to the empty-hohlraum shots Z442 and Z458 (Figure 2), the foam helps reduce the closure of the REH and permits the temperature of the small hohlraum to increase by ~7±5 eV to ~160 eV (Figure 3C).

The time-dependent temperature generated with the larger-diameter, more-massive PST (Z251) simulates the ~85 eV, ~10-ns *foot pulse* in the 6x7-mm^2 hohlraum (hashed region in Figure 3A). The temperature generated with the less massive target (Z441), in contrast, provides a reasonable match for simulating the temperature associated with the *first-step pulse* (hashed region in Figure 3B). Because the solid foam target permits the pinch to compress to ~0.5-mm radial dimensions, smaller hohlraums with reduced diameters can also be efficiently heated with this target and therefore driven to yet higher temperatures. Thus, alternatively, reducing the hohlraum size to 4x4-mm with this target enables the higher temperature associated with the *next step* to be also reached, as shown by the measured temperature history of Z459 with the hashed region in Figure 3C.

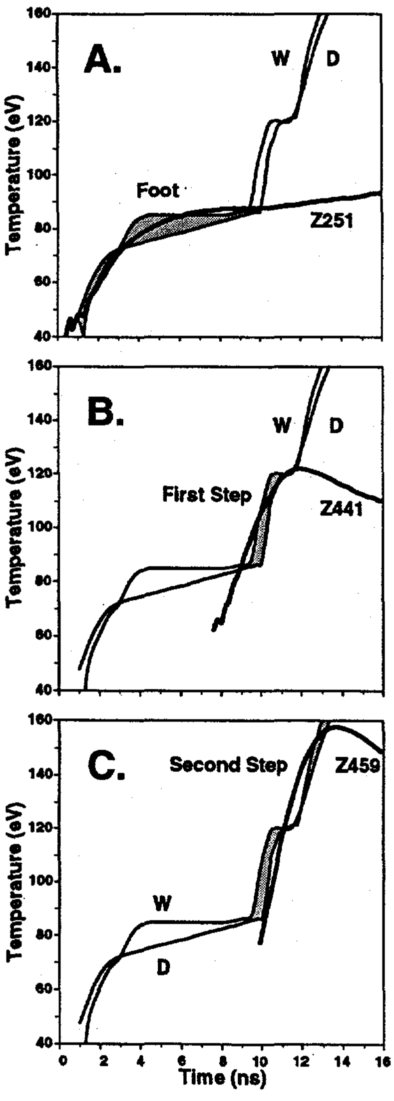

Figure 3: Comparison of two representative NIF radiation temperature profiles W and D with those measured for (A) Z251, (B) Z441, and (C) Z459.

Figures 4A and 4B plot the calculated axial temperature profile of the inside wall adjacent the diagnostic hole for the 6x7-mm (associated with Z387) and the 4x4-mm hohlraum (associated with Z442 and Z458), respectively, using a 3D-radiosity code assuming an estimated albedo of 0.8 [13]. Z387 is similar to Z441, except the foam PST was removed and the hohlraum had an additional diagnostic hole centered on its top. These changes increased the incident x-ray power through the REH by ~20% (from 11 to 13 TW), but also increased the axial temperature gradient and radiation loss, respectively. The temperatures measured are in excellent agreement with the calculations, providing confidence in the two-sided drive profiles also calculated in Figure 4 and discussed next.

Specifically, if instead of a single pinch (Figure 1A), the wire mass were to be distributed in two independent pinches of roughly half the length of a single one (in order to maintain a similar over-all load inductance) with the hohlraum sandwiched between the two (Figure 1B), the power entering the hohlraum should be roughly

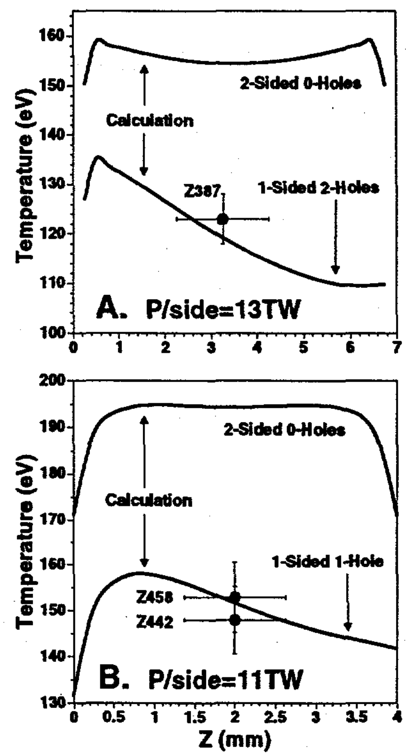

Figure 4: Calculated axial temperature profiles for one- and two-sided x-ray drives for (A) 6x7-mm and (B) 4x4-mm hohraums, showing the data taken corresponding to the one-sided drive.

doubled because the on-axis power is generated primarily near the pinch ends. The peak temperature associated with this single-feed, but now two-sided x-ray drive could then be increased to ~155 eV for the 6x7-mm hohlraum or ~195 eV for the 4x4-mm hohlraum, with a significant improvement in temperature uniformity This two-sided arrangement would thus permit greater fidelity NIF studies to be performed, and importantly, permit the generation of a measurable number [7] of DD neutrons to be generated in Be-coated capsules.

Even with the asymmetry of a Z459-type drive geometry and temperature, RMHC calculations suggest that ~10^{11} neutrons could be produced from a 2-mm diameter D_2-filled capsule having a 70-μm thick Be ablator. With such a source, meaningful neutron diagnostic and capsule fabrication studies could begin [8]. Here the burn time is long (~1 ns), the diameter big (~100 μm), and temperature low (~1 keV). Such data would complement that obtainable from the short burn time (~50 ps), small diameter (~10 μm), hot (~10 keV) implosions available on OMEGA.

IV. HOHLRAUM CHARACTERISTICS

RMHC simulations such as those of Reference 16 are used to understand the underlying dynamics of the implosion, and to provide insight into the radiation and plasma fields inside the hohlraum. These simulations are 2-D integrated calculations that take into account the development of the Rayleigh-Taylor instability in the r-z plane of the imploding load, energy generation as the plasma assembles on the PST, and radiation transport to the hohlraum. The simulation of Z441 (Figure 2B) at the time of peak temperature, for example, shows that the radius of the REH is reduced by 0.2 mm, the gold wall has expanded radially by ~0.25 mm, and the tungsten plasma has expanded axially through the ~0.5-mm depth of the REH, with only CH plasma entering the hohlraum. At this time, the gold walls of either the 6x7-mm or the 4x4-mm hohlraum expand inward at the rate of ~0.2 mm/ns. In contrast, the radius of the diagnostic hole (where the optical depth > 1) closes at the rate of ~0.09-0.12 mm/ns, with the upper limit associated with the 4x4-mm hohlraum. And for the duration of the temperature rise, the density of the CH plasma in the hohlraum above the REH remains low (~10^{-3} g/cm^3).

V. CONCLUSIONS

In conclusion, the measurements made with this single-sided-drive, static-wall-hohlraum geometry on Z have shown the ability to generate temperature pulse shapes of utility to pre-NIF studies up to peak temperatures of ~130 eV in full ignition-scale hohlraums, and ~160 eV in reduced-scale hohlraums. The RMHC simulations, like the measurements [10] suggest that over useful radiation drive times, the main volume of the hohlraums remains relatively free of z-pinch plasma. Static radiosity calculations indicate that implementing a two-sided drive can substantially enhance the utility of this geometry. Under these conditions, peak temperatures of ~155 and ~195 eV are expected, for the 6x7-mm or 4x4-mm hohlraum, respectively.

ACKNOWLEDGEMENTS

M. K. Matzen and J. P. Porter are thanked for programatic support; S. Dropinski, T. L. Gilliland, R. E. Hawn, D. Jobe, J. S. McGurn, J. S. Seamen, W. A. Stygar, J. A. Torres, and the Z crew are thanked for their dedicated technical support; and M. K. Matzen and M.E. Cuneo are thanked for their careful review of the paper.

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*Sandia is a multiprogram laboratory operated by the Sandia Corp., a Lockheed Martin Company, for the U.S.DOE under Contract No. DE-AC04-94AL85000.