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Energy transfer between lasers in low-gas-fill-density hohlraums

A. L. Kritcher, J. Ralph, D. E. Hinkel, T. Döppner, M. Millot, D. Mariscal, R. Benedetti, D. J. Strozzi, T. Chapman, C. Goyon, B. MacGowan, P. Michel, D. A. Callahan, and O. A. Hurricane
Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, California 94551-0808, USA

We investigate cross-beam energy transfer (CBET), where power is transferred from one laser beam to another via a shared ion acoustic wave in hohlraums with low-gas-fill density as a tool for late-time symmetry control for long-pulse (greater than 10 ns) inertial confinement fusion (ICF) and laboratory astrophysics experiments. We show that the radiation drive symmetry can be controlled and accurately predicted during the foot of the pulse (until the rise to peak power), which is important for mitigating areal density variations in the compressed fuel in ICF implosions. We also show that the effective inner-beam drive after CBET is much greater than observed in previous high-gas-filled-hohlraum experiments, which is thought to be a result of less inverse bremsstrahlung absorption of the incident laser light and reduced (by more than 10 times) stimulated Raman scattering (and Langmuir wave heating). With the inferred level of inner-beam drive after transfer, we estimate that more than 1.25 times larger plastic capsules could be fielded in this platform with sufficient laser-beam propagation to the waist of the hohlraum. We also estimate that a full-scale plastic capsule, 1100 μm in capsule radius, would require $\sim$1–2 Å of 1ω wavelength separation between the outer and inner beams to achieve a symmetric implosion in this platform.

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I. INTRODUCTION

Laser-driven multiple-millimeter x-ray-radiation environments lasting longer than 10 ns are relevant for inertial confinement fusion (ICF) experiments [1,2] and laboratory astrophysics experiments [3,4]. These long-duration radiation drives are achievable at the National Ignition Facility (NIF) [5] using laser-irradiated gold or uranium hohlraums. However, time-dependent asymmetries in these radiation environments are difficult to diagnose and control due to plasma filling of the hohlraum and impaired late-time laser-beam propagation [6–10]. Experiments using ramped laser pulses lasting tens of nanoseconds to study material properties require symmetry for accurate interpretation of radiography or velocimetry data. In addition, radiation drive asymmetries are important for ICF experiments and are thought to have been one of the limiting factors in the performance of the successful HiFoot campaign [2,11–13], which mitigated instabilities at the ablation front with a higher picket radiation temperature than previous experiments. Simulations suggest that if these hohlraum drive asymmetries were mitigated, the neutron yield could be further increased [14,15].

Such experiments transferred power between crossing laser beams [cross-beam energy transfer (CBET)] [16] operating at different wavelengths via stimulated Brillouin scattering (SBS) [17], a three-wave process between two crossing beams and an ion acoustic wave generated by their beat wave. This process has been utilized to modify radiation drive symmetry during the peak of the pulse in high-gas-filled hohlraums (0.96–1.6 mg/cm^3 He) [11,18–21]. However, symmetry during the early part of the drive was difficult to predict and control due to laser-plasma interactions. Controlling these early-time asymmetries is important because they can cause significant variations in the areal density of the compressed shell and can limit compression and heating of the deuterium-tritium fuel in ICF experiments. In addition, swings in the radiation flux symmetry as a function of time can result in swings between the in-flight and hot-spot symmetry, resulting in an overestimation of the amount of CBET needed to drive a round implosion.

Following these experiments, there has been a significant effort to control time-dependent radiation drive asymmetries without the use of CBET, which has been achieved through shorter duration experiments using alternate higher-density high-density-carbon (HDC) and beryllium ablators [22–25] and smaller capsules [26]. These experiments have increased the size of the hohlraum compared to the capsule size to improve inner-beam propagation and moved to lower hohlraum-gas-fill densities (0.3–0.6 mg/cm^3 He) to increase laser energy coupling to the hohlraum [27,28]. The early radiation drive asymmetries, before the peak of the radiation drive, were significantly improved compared to previous experiments [26]. However, late-time laser-beam propagation to the waist of the hohlraum remains a concern for fielding larger capsules and for experiments using plastic ablators that require longer pulses. For example, implosions using plastic ablators at full scale (1100 μm) with no intentional CBET resulted in elongation of the dense shell in flight and final hot-spot shape along the equatorial plane (oblate implosion) which is expected to significantly impact the neutron yield (by more than 70% according to simulations [7]).

Here we demonstrate the effectiveness of using CBET in hohlraums with low-gas-fill density (0.6 mg/cm^3 He) that have demonstrated high laser coupling [26,28], to increase late-time inner-beam propagation. We also show that we can accurately predict and control early-time drive asymmetries compared to those seen in high-gas-filled hohlraums. In these

experiments, energy was transferred from the outer beams to the inner beams using a 1ω wavelength separation $\Delta\Lambda$ of 2 and 5.5 Å between the outer and inner beams. This transfer results in enhanced late-time drive at the waist of the hohlraum with the intent to drive the implosion more prolate, or elongated along the axis of the hohlraum. Measured shock velocities along the pole and equator [29,30] during the foot of the laser pulse (until the rise to peak power) were predictable and agree well with simulations. Measured in-flight implosion symmetry [31] suggests a significant increase in effective inner-beam drive after CBET compared to previous experiments and compared to preshot predictions. Given this enhanced level of late-time drive at the waist of the hohlraum, we provide an estimate for the largest capsule we could drive round in this platform and the level of $\Delta\Lambda$ required to achieve a round implosion.

II. EXPERIMENTAL CONFIGURATION

The experiments were performed at NIF using plastic glow discharge polymer (GDP) ablators with a graded Si dopant layer to shield against preheat from hohlraum x rays. The outer diameters of the capsules were 1110 μm and the ablator thicknesses were 175–188 μm. The capsules were filled with liquid D2 for the shock tuning experiments, N161103-001 and N161006-002, and a gas mixture of D ^{3}He for the experiment to measure in-flight symmetry using x-ray radiography, N170706-001 [see Fig. 1 (bottom right)]. Shot N161006 used a wavelength separation of $\Delta\Lambda = 2$Å between the inner and outer beams and N161103 and N170706 operated at $\Delta\Lambda = 5.5$Å. Shot N170706 also separated the inner cone wavelengths, or three-color $\Delta\Lambda$ (see Table I). The hohlraum was 6.72 mm in diameter, 11.24 mm in length, and had

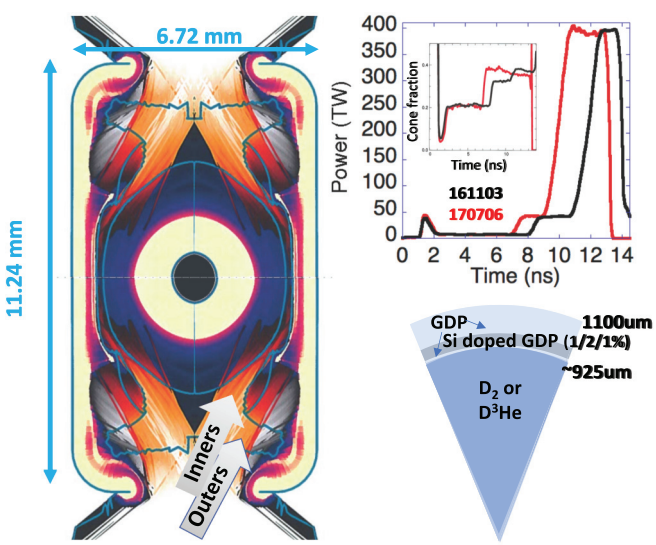

FIG. 1. Shown on the left is a schematic of the hohlraum with simulations overlaid showing the trajectory of the inner and outer beams. The bottom right diagram shows the GDP capsule configuration, including the silicon-doped layers. The top right is a graph of the laser powers vs time for the shock timing (N161103, in black) and radiography (N170706, in red) shots. The inset shows the measured cone fractions.

TABLE I. Operation wavelengths for the inner (23° and 30°) laser-beam cones and outer (44° and 50°) laser-beam cones.

	1ω wavelength (Å)		
Shot number	23° cone	30° cone	44° and 50° cones
N161006-002	10530.5	10530.5	10528.5
N161103-001	10529.8	10529.8	10524.3
N170706-001	10530.5	10529.8	10524.3

3.64-mm-diameter laser entrance hole (LEH). The hohlraum wall material was depleted uranium (DU) for N161103 and gold-lined DU for N170706. A schematic of the hohlraum configuration with example simulations overlaid is shown in Fig. 1 (see also Ref. [32] for more details regarding the experimental configuration and results).

Laser powers vs time for the tuning shots operating at $\Delta\Lambda = 5.5$Å (N161103 and N170706) are shown in Fig. 1. Differences in the pulse shapes were made to separate the shock mergers for N161103 [30], account for the change in hohlraum wall material, and improve ablation front stabilization via a stronger first shock for N170706. The total energy of shot N161103 was limited compared to N170706 due to the risk of laser light backscatter into the optics. Both pulses delayed the outer beams by 1.2 ns compared to the inner beams to provide time for the inner beams to blow down the window covering the LEH. The cone fractions during the foot of the pulse (until the rise to peak power at ~11 ns) were designed to mitigate early-time asymmetries induced by the cross-beam energy transfer that occurs over the duration of the entire pulse (see the inset of Fig. 1).

III. RADIATION HYDRODYNAMICS SIMULATIONS

The hohlraum radiation drive and capsule were modeled together using the radiation hydrodynamics code HYDRA [33] in two dimensions with an axis of symmetry along the hohlraum axis. The radiation drive was calculated using the so-called high-flux model [34] with detailed configuration accounting (DCA) nonlocal thermodynamic equilibrium atomic physics and Spitzer-Härm electron thermal conduction with a flux limiter of $0.15 n_e T_e v_{Te}$. Here n_e is the electron density, T_e is the electron temperature, and v_{Te} is the electron thermal velocity. The emissivities and opacities were calculated inline using DCA for $T_e > 300$ eV and using local thermodynamic equilibrium tables elsewhere. Tabular equations of state, the Livermore Equation of State (LEOS), and tabular opacities (OPAL) [35] were used to model the GDP ablator.

The as-shot laser energies and backscatter [36] were measured and used as inputs to the simulations. Multipliers on the laser power during the foot of the pulse [37] were determined from separate calibration experiments with no intentional CBET [38]. In addition, a laser power multiplier applied during the peak of the drive was needed to match the time of maximum hot-spot x-ray emission [39] for shot N170706 (14.7 ± 0.04) while correcting for the loss of drive due to the hohlraum diagnostic windows not present in the simulations. The time-dependent CBET was calculated from simulations with the full laser power and included in subsequent simulations where the incident laser power was modified to

account for backscatter and to reproduce measured shock velocities [16]. This method has been shown to overestimate inner-beam drive in experiments at high hohlraum-gas-fill density and where there is significant laser backscatter on the inner beams [stimulated Raman scattering (SRS), i.e., the process whereby incident laser light resonantly scatters off Langmuir waves] [40]. Impact of laser-beam absorption via inverse bremsstrahlung, energy into Langmuir waves, or reabsorption of backscattered light are not included, which reduce the amount of inferred transfer but better approximates low-gas-fill hohlraum experiments (as described here), with more than 10 times lower SRS.

During the foot of the pulse we do not use artificial multipliers on the symmetry. However, during the peak of the drive we apply an empirically determined saturation clamp ($\delta n_e^{\rm sat}/n_e$) on the level of electron density fluctuation associated with the ion acoustic wave, effectively reducing CBET. Such an artificial clamp is routinely used in radiation hydrodynamic modeling to match experimental observables (see, e.g., [41,42]) and is still required (albeit at a larger value) when SRS and CBET are self-consistently modeled inline [40]. In the foot of the drive we use $\delta n_e^{\rm sat}/n_e = 1 \times 10^{-2}$, which is effectively unsaturated since the plasma waves driven by CBET typically are in the range $\delta n_e/n_e = 1\times10^{-4}$–$1\times10^{-3}$ [43].

IV. RESULTS AND DISCUSSION

Measured shock velocities as a function of time are shown in Fig. 2 for shot N161103 (black curves where the error is denoted by the width), with distinct features corresponding to the first shock breaking out of the ablator into the D2 (∼9.3 ns), the merger of the first and second shocks (∼11.9 ns), and the merger of the first and second shocks with the final shock (∼12.9 ns). Measurements of shock velocities along the polar direction [Fig. 2(a)] and equatorial direction [Fig. 2(b)] provide information on the symmetry of the shocks as a function of time. Loss of data occurs at velocities exceeding ∼140 km/s due to preheating from self-emission of the shock front. The data are well matched by simulations (red curves) during the foot of the pulse (until the final shock merger) using a nearly unsaturated level of cross-beam energy transfer and without the need for artificial symmetry multipliers. This model also accurately reproduced measured shock velocities at lower levels of wavelength separation $\Delta\Lambda = 2$Å (shot N161006-002). In contrast, matching measured shock velocities in high-gas-fill hohlraums, where modeling of beam propagation and plasma conditions was difficult, required artificial multipliers on the drive symmetry during the foot of the pulse.

However, a saturation clamp on CBET during the peak of the pulse was required to match the final shock mergers and velocities (see the insets in Fig. 2 for expanded views of the final mergers). Due to sensitivity of the diagnostic a range of $\delta n_e^{\rm sat}/n_e$ [from 5×10^{-4} (green) to 2×10^{-3} (red)] applied during the rise and peak of the pulse, corresponding to ∼1.36–1.6 times average effective inner beam power increase, matched experimental data. Here higher $\delta n_e^{\rm sat}/n_e$ corresponds to increased transfer from the outer to inner beams and a faster final shock along the equator. To narrow down this range, a more sensitive follow-on tuning experiment was fielded where

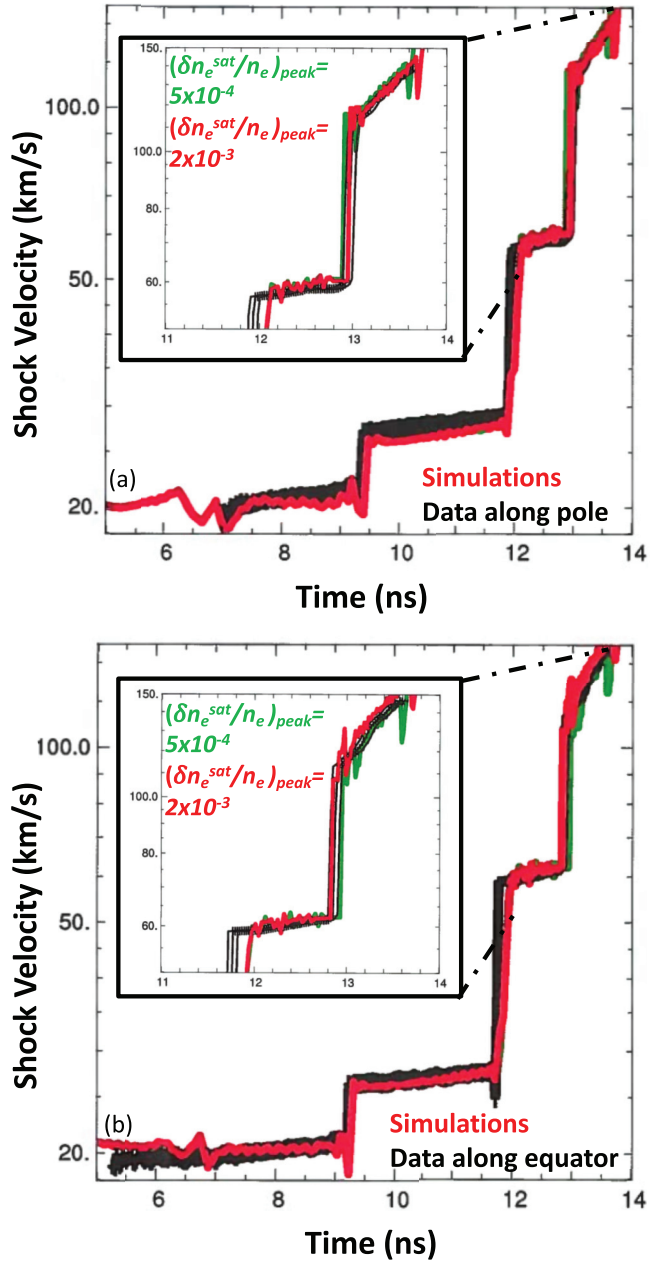

FIG. 2. (a) Simulated shock velocities (km/s) vs time in the polar direction (red and green) compared to experimental data (black) for shock timing shot N161103. (b) Simulated (red and green) vs measured (black) shock velocities along the equatorial direction for N161103. The insets are expanded views of the final shock mergers to show model sensitivity. The three experimental curves correspond to the uncertainty range of the measurement.

the dense shell symmetry at a convergence of ∼5 (in flight) and hot-spot core emission symmetry were measured.

Figure 3 shows simulated radiographs of the dense shell in flight for shot N170706 at a radius of ∼200 μm, along with simulated Legendre decompositions ($l = 2$ component) of the limb minimum transmission contour (red points) as a function of $\delta n_e^{\rm sat}/n_e$ applied during the peak of the pulse. The x axis at the top of the plot is the amount of calculated increase in average inner-beam power as a result of the cross-beam

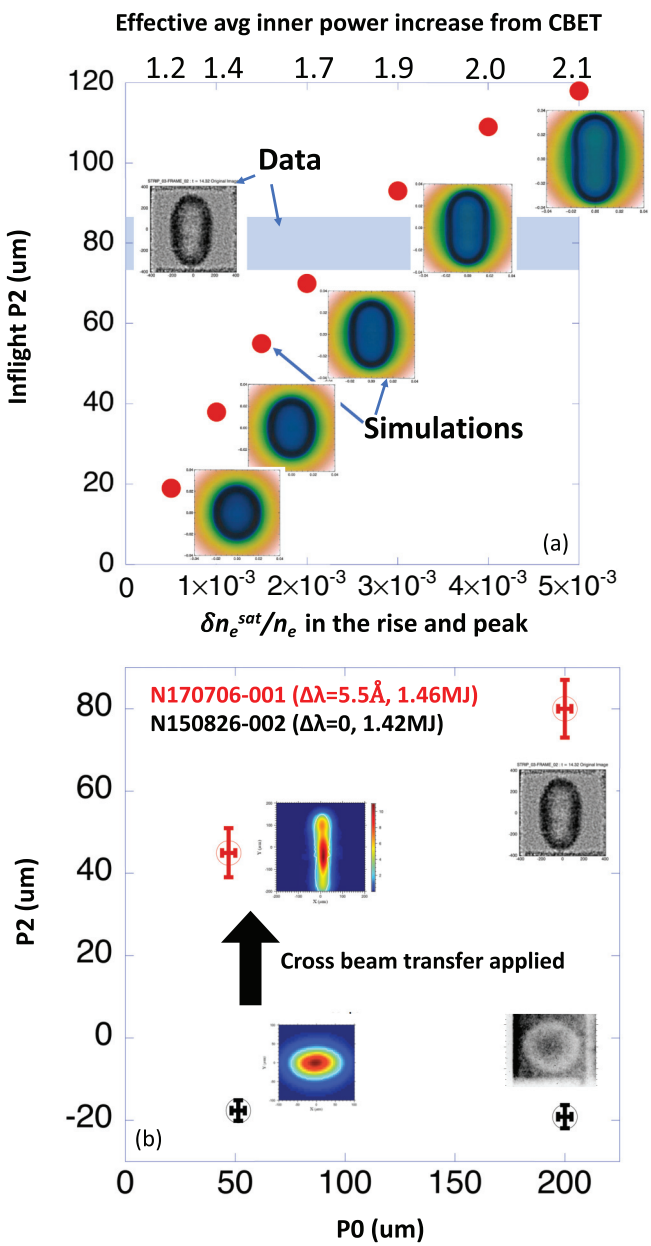

FIG. 3. (a) Simulated radiographs and P2 decompositions (red points) of the dense shell inflight (radius near 200 μm) for shot N170706 vs effective average power increase on the inner beams as a result of CBET (top x axis). The simulations saturate the amplitude of the ion acoustic wave ($\delta n_e^{\rm sat}/n_e$) to vary the x axis (shown on the bottom x axis). Also shown is the measured radiograph and P2 with a band that denotes the uncertainty. (b) Decompositions of the measured P2 inflight ($P0 = 200$ μm) and near peak compression ($P0 \sim 50$ μm) for low-gas-fill hohlraum experiments with no intentional CBET (N150826, $\Delta\Lambda = 0$Å) and with CBET (N170706, $\Delta\Lambda = 5.5$Å).

energy transfer. The measured radiograph at ~200 μm is also shown, along with a blue band corresponding to the $l = 2$ (P2) moment of the measured limb minimum transmission contour with error bars. A range of $\delta n_e^{\rm sat}/n_e = (2\text{–}3) \times 10^{-3}$ reproduces the measured in-flight symmetry which overlaps with the upper bound of the range used to match the final shock symmetry for N161103, when accounting for the changes made between the shots including the $\Delta\Lambda$ change. The calculated level of average inner-beam power increase during the rise and peak of the pulse for N170706 and $\delta n_e^{\rm sat}/n_e \sim (2\text{–}3) \times 10^{-3}$ is 1.67 (1.9 times), which is higher than calculated for HiFoot shot N140520 (1.26 times) operating at a hohlraum-gas-fill density of 1.6 mg/cm^3 He and similar wavelength separation, $\Delta\Lambda = 6.2$Å.

In addition, the effective inner-beam power was significantly increased compared to a benchmark experiment in a low-gas-fill hohlraum with no intentional CBET [26] (N150826, $\Delta\Lambda = 0$Å), which resulted in an oblate in-flight dense shell and hot spot [see Fig. 3(b)]. The change in $l = 2$ moment (P2) between the in-flight and hot-spot symmetry [44] (nonconformal P2) for N170706 is thought to be due to cooling of the outer regions of the hot spot. This experiment used the same target configuration and pointing, the same hohlraum-gas-fill density (0.6 mg/cm^3), similar laser energy (~1.42 MJ for N150826 vs ~1.46 MJ for N170706), similar pulse length (~13.6 ns for N150826 vs ~13.2 ns for N170706), and similar laser cone fraction during the peak of the pulse (~34% for N150826 vs ~35% for N170706). The main difference between these experiments was adjustment to the foot of the pulse to achieve symmetry for $\Delta\Lambda = 0$Å vs 5.5Å. Other diagnostics that support increased effective inner-beam drive after CBET include a significant increase in the measured inner-beam SBS [32,36,45] compared to experiments with no intentional transfer and increased hard-x-ray self-emission from interaction between the inner beams and the hohlraum wall near the equator [32,46].

The improved waist drive after in transfer in low-gas-fill hohlraums over that of high-gas-fill hohlraums is in part due to less inverse bremsstrahlung absorption of laser light along the beam path and reduced (greater than 10 times) SRS backscattered laser energy [32] (and Langmuir wave heating). Fewer superthermal electrons were also observed in these experiments compared to high-gas-fill hohlraums [22,32,47], which is consistent with the reduced SRS. Previous analysis of high-gas-fill-hohlraum experiments [40] speculated improved transfer for platforms with reduced SRS, which is demonstrated in this work. More self-consistent modeling of electron transport, CBET, and backscatter, though less important for the low-gas-filled hohlraums, should further mitigate the need for an empirically determined saturation level in simulations [40].

An excess of drive on the waist of the hohlraum can be used advantageously to drive larger capsules, which reduces the energy requirement for ignition due to higher convergence. Using $\delta n_e^{\rm sat}/n_e = (2\text{–}2.5) \times 10^{-3}$, we estimate that transfer to the inner beams, resulting in a 1.7–1.9 times increase in average laser power, could enable driving more than 25% larger capsules (exceeding 1400 μm in outer radius), with the same thickness, which could result in more than 2.5 times yield improvement from analytical scaling of yield with capsule size [48] and more if α heating is considered. For this design study $\Delta\Lambda = 5$Å between the inner and outer beams was used, consistent with N161103, which gave reduced laser backscatter compared to N170706 [45]. In addition, we estimate that a nominal full-scale capsule (1100 μm) with a 1.8-MJ laser pulse could be driven symmetrically with a wavelength separation of $\Delta\Lambda = 1\text{–}2$Å. The calculated hot

spot P2 using $\delta n_e^{\rm sat}/n_e = (2\text{–}2.5) \times 10^{-3}$ is -3 to 4.5 μm for $\Delta\Lambda = 1$Å, and 19–22 μm prolate for $\Delta\Lambda = 2$Å.

V. CONCLUSION

In summary, we have investigated cross-beam energy transfer from the outer to the inner beams in low-gas-fill hohlraums with the intent to increase the radiation drive at the waist of the hohlraum and drive the implosion more prolate. We found that the amount of effective increase in inner-beam drive at a given wavelength separation was higher than predicted and higher than observed in high-gas-fill experiments. We showed that the foot of the drive can be accurately predicted and controlled in low-gas-fill hohlraums in the presence of CBET without artificial multipliers on the radiation drive symmetry. With this magnitude of drive at the hohlraum waist, we estimated that large plastic capsules exceeding 1400 μm in outer radius could be driven symmetrically for a 1.8-MJ laser pulse. We also predicted that an outer to inner beam wavelength separation of 1–2Å would result in a round implosion for a nominal capsule outer radius of 1100 μm and a 1.8-MJ pulse.

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