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I. V. Igumenshchev,[1] D. H. Froula,[1] D. H. Edgell,[1] V. N. Goncharov,[1,2] T. J. Kessler,[1] F. J. Marshall,[1] R. L. McCrory,[1,2,3] P. W. McKenty,[1] D. D. Meyerhofer,[1,2,3] D. T. Michel,[1] T. C. Sangster,[1] W. Seka,[1] and S. Skupsky[1]

[1]*Laboratory for Laser Energetics, University of Rochester,*
250 E. River Road, Rochester, NY 14623-1299, USA
[2]*Department of Mechanical Engineering, University of Rochester, Rochester, New York 14623, USA and*
[3]*Department of Physics and Astronomy, University of Rochester, Rochester, New York 14623, USA*

Spherically symmetric direct-drive-ignition designs driven by laser beams with a focal-spot size nearly equal to the target diameter suffer from energy losses due to cross-beam energy transfer (CBET). Significant reduction of CBET and improvements in implosion hydrodynamic efficiency can be achieved by reducing the beam diameter. Narrow beams increase low-mode perturbations of the targets because of decreased illumination uniformity that degrades implosion performance. Initiating an implosion with nominal beams (equal in size to the target diameter) and reducing the beam diameter by $\sim$ 30% to 40% after developing a sufficiently thick target corona, which smooths the perturbations, mitigate CBET while maintaining low-mode target uniformity in ignition designs with a fusion gain $\gg 1$.

PACS numbers:

Direct-drive inertial confinement fusion (ICF) uses the energy of multiple laser beams to illuminate and implode a mm-scale capsule containing cryogenic nuclear fuel [1, 2]. Fusion reactions are initiated in the central hot spot when the capsule reaches maximum compression. One of the key physical conditions for ignition (i.e., getting fusion gain $G > 1$, where G is the ratio of the fusion energy to laser energy E_L) is to achieve a high implosion hydrodynamic efficiency $\eta = E_{\mathrm{kin}}/E_L$, which characterizes the conversion of E_L to kinetic energy E_{kin} of the imploding capsule shell. This condition requires that the shell velocity exceed a minimum threshold value $V_{\mathrm{imp}} \approx 3 \times 10^7$ cm/s, while maintaining a fuel areal density $\rho R \gtrsim 0.3$ g/cm^2 during maximum target compression [3].

Direct-drive implosion experiments are conducted on OMEGA [4] and National Ignition Facility (NIF) [5] laser systems operating at $\lambda_L = 351$ nm with on-target overlapped laser intensities $I_L \sim 10^{14} - 10^{15}$ W/cm^2. The laser absorption in the target corona is dominated by inverse bremsstrahlung. To provide the best illumination uniformity, the focal-spot radius of laser beams R_b is taken nearly equal to the target radius R_t, $R_b/R_t \approx 1$ [6]. Here, R_b is defined to encircle 95% of the beam energy. Implosion simulations, assuming energy losses due to only radiation and thermal expansion of the corona, predict $\eta \approx 6\%$. This hydrodynamic efficiency is sufficient to achieve robust ignition ($G \gg 1$) in designs using $E_L \gtrsim 1$ MJ [3, 7]. Recent studies have shown that cross-beam energy transfer (CBET) [8] resulting from stimulated Brillouin scattering (SBS) [9] can cause energy losses reducing η by $\sim$ 20% to 30% [10, 11].

CBET removes energy from incoming light rays that interact with ion-acoustic waves in low-electron-density regions ($n_e \sim 0.2 - 0.3\ n_{\mathrm{cr}}$, where $n_{\mathrm{cr}} = 9 \times 10^{21}$ cm^{-3} is the critical density) of the target corona [8]. The SBS gain responsible for CBET is maximum for incoming center-beam rays and is proportional to the intensity of outgoing rays from edges of opposing beams. Therefore, reducing the intensity at beam edges, or reducing R_b, reduces CBET [8].

Spherically symmetric implosion experiments on OMEGA employing laser beams with small on-target focal spots (which can be defocused to larger spots) were conducted to study the regime where R_b/R_t takes the values of 0.5 to 1.1. The results showed the predicted increases in laser absorption (via scattered-light measurements) and implosion velocity (via bang time and shell trajectory measurements) when reducing R_b/R_t [10]. An analysis of the uniformity of these implosions performed with the help of self-emission x-ray images found large perturbations with the dominant mode $L = 10$ in the case of small R_b/R_t [10]. The latter finding suggests that small-radius beams introduce significant low-mode perturbations to the targets because of increased illumination nonuniformities (beam overlap). These perturbations reduce the implosion performance and compromise the improvements in laser coupling achieved with small-radius beams.

Spherically symmetric direct-drive-ignition designs suffer from CBET losses, so, therefore, CBET must be mitigated. For example, simulations predict that a particular 1.5-MJ direct-drive-ignition design [7] fails to ignite when CBET is considered (Fig. 1). Small-radius beams can be employed to mitigate CBET, but these beams introduce significant perturbations to the targets that degrade the implosion performance.

In this Letter, the concept of beam zooming is proposed to help mitigate CBET and maintain good target uniformity. Beam zooming reduces R_b/R_t from the ini-
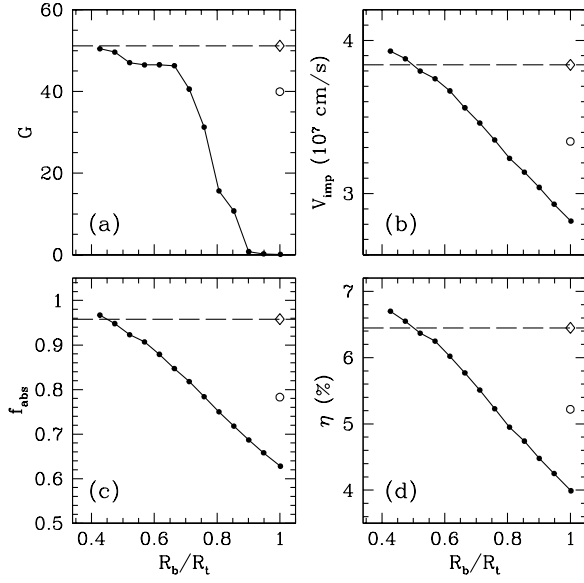
FIG. 1: Simulated (a) fusion gain G, (b) implosion velocity V_{imp}, (c) laser-absorption fraction f_{abs}, and (d) implosion hydrodynamic efficiency η for the 1.5-MJ spherically symmetric direct-drive implosion design [7] as functions of R_b/R_t. The black circles and solid lines correspond to simulations including CBET. The open diamonds and dashed lines show the performance in the nominal configuration (assuming $R_b/R_t = 1$) without CBET. The open circles represent the improvements in the nominal configuration with CBET, when CBET is mitigated employing two-color laser light [8].
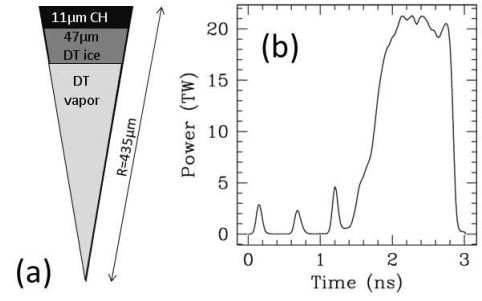

FIG. 2: Low-adiabat ($\alpha = 2$), 24-kJ triple-picket cryogenic OMEGA implosion design (shot 66613) used in 2-D *DRACO* simulations. (a) Target geometry and (b) laser power history. A spherically symmetric simulation of this design without CBET predicts a yield of 3.4×10^{14} neutrons.

tial nominal value of 1 to less than 1 after a geometrically thick ($\sim R_t$) target corona is developed. Before zooming, when the corona is geometrically thin and seeding perturbations from beam overlap is most efficient, illuminating targets with nominal-size beams provides the maximum uniformity. After zooming, CBET is mitigated and the thick corona has a sufficiently large conduction zone, which smooths the perturbations.

Figure 1 shows the simulated performance of the 1.5-MJ design in the nominal configuration ($R_b/R_t = 1$), which yields a gain $G = 52$ when CBET losses are not considered (open diamonds) and does not ignite ($G < 1$) when these losses are considered (black circles). This implosion is simulated using the one-dimensional (1-D) ICF hydrodynamic code *LILAC* [12], which includes a nonlocal thermal transport model [13]. CBET reduces the laser absorption fraction f_{abs} from 96% to 63%, V_{imp} from 3.8×10^7 to 2.8×10^7 cm/s, and η from 6.5% to 4%. Studies indicate that the loss of energy from CBET in direct-drive-ignition designs cannot be compensated by simply increasing E_L. This is because CBET is proportional to the intensity I_L [8] and any increase of E_L (which corresponds to increasing I_L in the fixed-radius targets) causes the proportional increase of CBET losses, making η a nearly constant or even a decreasing function of E_L. Robust direct-drive-ignition designs benefit from

the mitigation of CBET.

Improvements in the 1.5-MJ design with CBET when $R_b/R_t < 1$ are demonstrated in Fig. 1 (black circles). The implosion velocity V_{imp} [Fig. 1(b)], absorption fraction f_{abs} [Fig. 1(c)], and hydrodynamic efficiency η [Fig. 1(d)] gradually increase with decreasing R_b/R_t. All these quantities approach the values characteristic to the implosion without CBET (open diamonds) at $R_b/R_t \approx 0.5$. The gain curve shows a cliff around $R_b/R_t = 0.8$ [Fig. 1(a)]. This design is predicted to ignite with gain $G \approx 1$ at $R_b/R_t = 0.9$, and the gain is saturated near the maximum value, $G \approx 50$, at $R_b/R_t < 0.7$. The improvements in the implosion performance that results from reducing R_b can be partially attributed to mitigating CBET and partially to more-normal incident illumination of the target [14]. An analysis shows that the latter effect is less important than the improvements from mitigating CBET.

The effect of small-radius beams, which degrade the symmetry of implosion targets, was investigated using the two-dimensional (2-D) ICF hydrodynamic code *DRACO* [15]. *DRACO* simulations use the cryogenic, low-adiabat ($\alpha = 2$, where α is the ratio of the plasma pressure to Fermi-degenerated pressure), triple-picket OMEGA implosion design shown in Fig. 2. A flux-limited thermal-transport model [16] with a flux limiter $f = 0.06$ was employed. These simulations do not include the CBET model, which currently can be applied only in 1-D symmetric implosions. A 3-D model of CBET coupled with *DRACO* is being developed [17, 18]. Although 2-D simulations without CBET and with nominal-size beams are not as accurate, they can provide information about the perturbation levels. The simulations using small-size beams are not significantly affected by the absence of CBET because CBET is mitigated and should be small. The OMEGA laser uses 60 beams that are uniformly distributed over a sphere and arranged in hexagon and pentagon clusters. The laser deposition is calculated using a 3-D ray-trace algorithm and the actual OMEGA
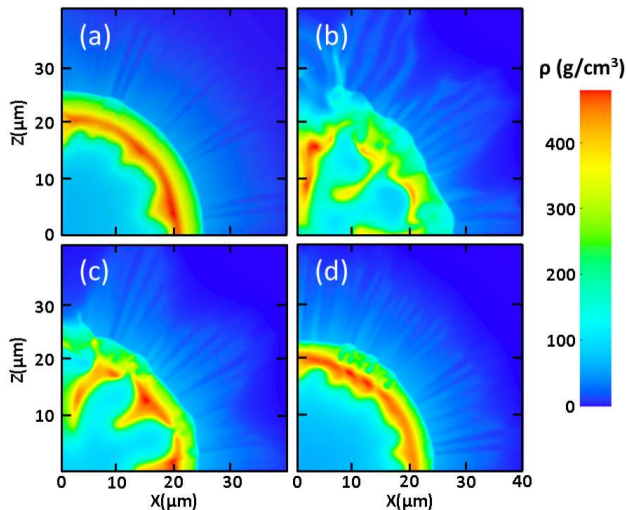
FIG. 3: (color online) Simulated distributions of the density at the peak neutron production for the implosion design shown in Fig 2. (a) Nominal-size beams, $R_b/R_t = 1$; (b) reduced-size beams, $R_b/R_t = 0.6$; (c) zooming beams from $R_b/R_t = 1$ to 0.6 at $t = 0.4$ ns [after the first picket, see Fig. 2(b)]; (d) same zooming beams as in (c), but at $t = 0.9$ ns (after the second picket).

beam-port geometry. The calculated energy deposition is then azimuthally averaged to be used in axisymmetric *DRACO* simulations. The current study considers perturbations from the beam overlap but not other laser-induced perturbations (such as laser imprint, and beam mispointing and mistiming).

Figures 3(a) and 3(b) compare the simulated distributions of density at the moment of maximum neutron production for the two cases of the nominal beams, $R_b/R_t = 1$, and small-radius beams, $R_b/R_t = 0.6$, respectively. In the nominal case, the perturbations are small and dominated by the $L = 10$ mode from beam overlap [Fig. 3(a)]. For the small-radius beams, large distortion of the target is apparent [Fig. 3(b)]. The areal density Σ_{rms} at the peak neutron production increases from 7% to 22% and the relative neutron yield (2-D yield over "clean" 1-D yield, or YOC) decreases from 95% to 26% in the nominal and small-radius beam cases, respectively.

Using the nominal-size beams at the begining of the implosion and zooming beam focal spots to smaller size after developing a geometrically thick ($\sim R_t$) corona around the target helps to reduce pertubations from beam-overlap nonuniformities and, simultaneously, mitigates CBET. There are two reasons why this technique is effective: First, the perturbations from beam overlap are developed mainly at the beginning of the laser pulse. The corona developed during the main laser drive forms an extended conduction zone. This zone is capable of efficiently smoothing perturbations from the laser, including the relatively large scale perturbations induced by beam

overlap. The geometrically thin corona existing at the beginning of the pulse cannot provide such a smoothing. Second, the study of CBET in OMEGA implosions showed that CBET is relatively weak at the beginning of the drive and takes its maximum value later in time, when the extended corona is developed [8]. Therefore, using the nominal laser beams ($R_b/R_t = 1$) at the beginning of implosions is not critical with respect to mitigating CBET and provides the best illumination uniformity at this critical moment when perturbations from the laser are most efficiently imprinted into the target. The later-time reduction of the beam diameter helps to mitigate CBET during the main drive, whereas the corresponding increase of beam-overlap illumination nonuniformities does not introduce significant perturbations to the target due to the smoothing effect of the corona.

The moment of zooming should be chosen to balance the reduction of target nonuniformities and mitigation of CBET. Zooming too early can compromise the uniformity and zooming too late can result in excessive energy losses related to CBET. Figures 3(c) and 3(d) show *DRACO* simulation results assuming a two-state zooming from $R_b/R_t = 1$ to 0.6 at two different moments, $t = 0.4$ ns (after the first picket) and 0.9 ns (after the second picket), respectively. The target is significantly distorted when zooming occurs just after the first picket, indicating that the target corona is not developed enough to smooth the perturbations. Zooming the beams after the second picket shows significant improvements in target uniformity. Zooming even later, after the third picket, shows about the same improvements as zooming after the second picket. Table I summarizes the simulation results showing YOC and areal density Σ_{rms} for the models assuming different zooming options: zooming after the first, second, and third pickets, and no zooming. These data indicate that the decrease of Σ_{rms} in the models with delayed zooming is anticorrelated with the increase of YOC. Zooming after the second and third pickets shows about the same relative implosion performance as in the case where the nominal-radius beams are used without zooming.

Table I. Summary of *DRACO* simulation results.

Zooming	R_b/R_t	YOC(%)	Σ_{rms}(%)
Not applied	0.6	26	22
After first picket	1.0 to 0.6	55	20
After second picket	1.0 to 0.6	89	6
After third picket	1.0 to 0.6	88	9
Not applied	1.0	95	7

Potential schemes to implement zooming of the focal spot on target involve modifications to the spatial coherence of the laser that cause broadening in the beam's far field [19]. The most practical method for implement-

ing zooming on modern laser systems (e.g., OMEGA and NIF) appears to be time-dependent phase conversion. A new phase-plate design, referred to as a zooming phase plate (ZPP), is proposed. ZPP's will have a radial phase transition where the central area will produce a larger, low-order Gaussian focal spot, while the outer area will produce a smaller, high-order Gaussian focal spot. This configuration requires a smaller-diameter beam during the pickets and a mid-section cutout of the near field during the drive pulse [20].

The beam-zooming technique can benefit from implementing it into a two-color laser system. This system alone can reduce CBET by a factor of ~ 2 (see open circles in Fig. 1) if the wavelength separation of the colors $\Delta\lambda > 5\mathring{A}$ (for $\lambda_{\mathrm{L}} = 351$ nm) [8]. Simultaneously employing the beam zooming and two-colors techniques will make it possible to use less-restrictive requirements for the zooming ratio and, therefore, improve implosion uniformity while maintaining low CBET.

The beam-zooming technique applies to spherically symmetric illumination and might not be applicable to the polar-drive configuration [21]. Mitigation strategies optimized for polar drive are under investigation [17, 18].

In summary, CBET reduces the implosion velocity in directly driven targets below the ignition-relevant values and must be mitigated to obtain robust direct-drive-ignition designs. Implosion experiments on OMEGA demonstrated that laser beams with on-target focal spots smaller than the target diameter mitigate CBET. Simulations suggest that using beams with $R_{\mathrm{b}}/R_{\mathrm{t}} < 0.7$ in the 1.5-MJ direct-drive-ignition design recover the majority of the implosion velocity lost to CBET. Such a reduction of $R_{\mathrm{b}}/R_{\mathrm{t}}$ introduces large-amplitude, low-mode perturbations to the targets because of increasing beam-overlap illumination nonuniformities. Experiments and simulations indicate that these perturbations degrade the implosion performance. Beam zooming is proposed to overcome this problem. Employing beams with the nominal $R_{\mathrm{b}}/R_{\mathrm{t}} = 1$ at the beginning of the laser pulse and later reducing the beam radius to $R_{\mathrm{b}}/R_{\mathrm{t}} < 0.7$ during the main drive can improve low-mode uniformity of the target while maintaining low-energy losses relating to mitigating CBET. The performance of 2-D axisymmetric OMEGA implosions assuming perturbations from optimally zooming beams is predicted to be almost as good as the performance of the corresponding 1-D, spherically symmetric implosions. The practical way of implementing beam zooming is considered using ZPP's.

The analysis of perturbations performed in this paper is limited only to 2-D axisymmetric modes and does not include the effects of CBET. It is unlikely that more accurate 3-D simulations including CBET will change the qualitative conclusions of this analysis, but some quantitative changes are expected. For example, 3-D perturbations will grow faster and introduce more damage to implosions. Further developments of the zooming technique will require investigating other laser-induced perturbations attributable to ZPP's (e.g., laser imprint). These issues will be addressed in future studies.

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