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Target areal density (ρR) asymmetries in OMEGA direct-drive spherical implosions are studied. The rms variation $\langle \delta\rho R\rangle/\langle \rho R\rangle$ for low-mode-number structure is approximately proportional to the rms variation of on-target laser intensity $\langle \delta I\rangle/\langle I\rangle$ with an amplification factor of ~ ½(C_r -1), where C_r is the capsule convergence ratio. This result has critical implications for future work on the National Ignition Facility (NIF) as well as OMEGA.

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Attaining ignition and high gain in inertial confinement fusion (ICF) requires that deuterium-tritium (DT) filled capsules be spherically imploded to high temperature and density [1-3]. "Hot spot" ignition, where a capsule is compressed so as to form two different regions: a small mass of low density, hot (~10 keV) fuel at the center surrounded by a larger mass of high density, low temperature fuel, is the leading method envisioned to achieve this goal. Shock coalescence "ignites" the hot spot, and a burn wave propagates into the main fuel region. Success requires a symmetric implosion, because significant deviation from spherical symmetry will result in shock dynamics that do not lead to ignition. In the direct-drive approach to ICF, where implosion occurs in response to a large number of high-power, individual laser beams illuminating the surface of a capsule, the requirement for spherical implosion imposes severe constraints on the uniformity of the laser drive [1-3] and on the sphericity of the capsule.

Illumination nonuniformities, coupled with initial capsule imperfections, lead to distortions in the compressed capsule. High-mode-number perturbations (ℓ >10) are primarily imprinted by nonuniformities within individual laser beams [4,5]. During both the acceleration and deceleration phases, these perturbations are amplified by Rayleigh–Taylor (RT) instabilities and grow exponentially until reaching saturation at amplitudes of ~ $4R/\ell^2$ (R is the capsule radius); thereafter they grow linearly [6]. Low-mode-number asymmetries (ℓ ≤10) result primarily from either drive-pressure asymmetry, due to nonuniformity in on-target laser intensity, or to capsule fabrication asymmetry [4,5]. These secular modes grow linearly throughout the entire implosion, largely due to Bell-Plesset (BP) related convergence effects [7].

A major effort has been made in current ICF research to reduce target illumination nonuniformity and capsule imperfections. Characterization of these efforts requires measurement of any deviations from spherical symmetry in the assembled capsule mass, or areal density (ρR) [8]. Previous work relied on numerical simulations to predict the conditions under which asymmetries may develop, and x-ray imaging to provide information about emission symmetry [9]. Quantitative experimental information about ρR asymmetries has not been available, however, until recent experiments [10-11] on OMEGA [12] using novel charged-particle spectrometry techniques [13]. These experiments have resulted in the first studies of low-mode-number ρR asymmetries at the time of fusion burn for direct-drive spherical implosions (the diagnostic technique is sensitive to structure with mode numbers ℓ < 5). Conclusions from these experiments are that changes in laser-intensity distributions result in changes in ρR asymmetries, while capsule imperfections do not seem to be a dominant factor under current conditions [14]. In this Letter we present new studies showing quantitatively, for the first time, how the amplitude of ρR asymmetries is directly correlated with the amplitude of asymmetries in time-averaged, on-target laser intensity, I, for ablatively-driven implosions. The resulting scaling law is based on both theoretical implications of capsule convergence and experimental data, and has implications for future work on the National Ignition Facility (NIF) [1] as well as OMEGA.

The terminology that will be used is that $\langle\rho R\rangle$ and $\langle I\rangle$ are averages over angle, $\delta\rho R$ and δI are deviations from the average at a given angle, and $\langle\delta\rho R\rangle$ and $\langle\delta I\rangle$ are rms averages over angle.

Illumination asymmetries on OMEGA are generated by several sources. First there are differences in the time-integrated energies delivered by the 60 individual laser beams, which can be characterized by an rms beam energy imbalance σ_b which tends to be in the range $\sigma_b \lesssim 3\%$ [15]. But the beams overlap on the capsule surface, and the overlap reduces the net energy nonuniformity to a value σ_e which can be estimated from a typical measured beam profile shape and the theoretical positions of the individual beam centers; $\sigma_e \sim 0.8$-1.5% rms. The total illumination nonuniformity on the capsule surface is higher than σ_e because of other contributing factors, and can be estimated as $\langle\delta I\rangle/\langle I\rangle \approx \sqrt{\sigma_e^2+\sigma_s^2+\sigma_p^2+\sigma_o^2}$. The component σ_s, typically ~ 1% rms [16], is due to deviations of individual beam shape profiles from that assumed in calculating σ_e. The component σ_p (typically ~ 1.9% rms [16]) results from errors in the pointing of individual laser beams, and σ_o (typically ~ 1% rms [16]) is an additional contribution from any offset of the capsule center from the center of the target chamber (σ_o is ~ 0.2 times the offset in μm [16]). Target offset results in drive asymmetry with strong ℓ =1 and 2 modes. This is demonstrated in Fig. 1, which displays a 2-dimensional (2D) simulation from the hydrodynamic code *DRACO,* incorporating the measured beam imbalance and other nominal experimental conditions for an implosion with 50-μm offset from target-chamber center (TCC). The simulation indicates strong correlation between drive asymmetry and ρR asymmetry, which will be addressed empirically below. These low-mode capsule perturbations cannot be smoothed by the effects of lateral energy flow in the form of transverse thermal conduction [17] because the scale-length of the perturbations is typically much longer than the separation between the critical surface and the ablation surface.

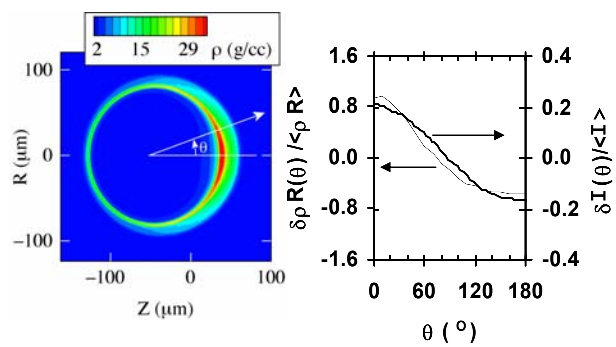

FIG.1. (a) Density contours at a time of peak burn (~1.9 ns) for an implosion of a capsule offset by 50 μm from TCC, simulated using the 2D code *DRACO* for conditions of shot 26646 (23 kJ of laser energy in a 1-ns square pulse applied to a capsule with 15 atm of D_2 in a 20-μm CH shell). (b) The target offset results in drive asymmetry with strong ℓ =1 and 2 modes which generates a correlated ρR asymmetry.

The amplitude of asymmetries in ρR is quantitatively correlated with the amplitude of asymmetries in time-averaged, on-target laser intensity *I*. Both theoretical and experimental approaches have been used to understand the correlation. Theoretically, a scaling law for predicting how measured ρR asymmetries relate to $\langle\delta I\rangle/\langle I\rangle$ can be derived from considerations of implosion dynamics, assuming that ρR asymmetries are seeded by the illumination asymmetries and modified due to effects of capsule convergence. The growth rates of low-ℓ-number perturbations due to RT instabilities are small ($\propto\sqrt{\ell}$). To first order the angular variations in acceleration rates (g) during both acceleration and deceleration phases of an implosion can be written $\langle\delta g\rangle/\langle g\rangle\approx\langle\delta V_{imp}\rangle/\langle V_{imp}\rangle$ [1], where $V_{imp} = V_{imp}(t)$ is the capsule implosion velocity. Starting with $(R_0-R) \approx V_{imp}t_{imp}$ and considering implosion dynamics one obtains

$$-\frac{\langle \delta R\rangle}{\langle R\rangle} \approx \frac{\langle \delta V_{imp}\rangle}{\langle V_{imp}\rangle}(C_r - 1). \quad (1)$$

In this expression C_r is the convergence ratio $C_r \equiv R_0/\langle R\rangle \approx \sqrt{\langle \rho R\rangle / f\rho_0 R_0}$, where ρ_0 and R_0 are the initial shell density and radius, and f is the fraction of shell mass not ablated (which can be estimated from "burn-through" experiments [18]). One obtains $-\langle \delta R\rangle/\langle R\rangle \approx \frac{1}{2}\langle \delta\rho R\rangle/\langle \rho R\rangle$. V_{imp} is a function of laser intensity on target for direct-drive implosions with $V_{imp} \propto I^{1/3}\ln(m_0/m)$, where $m(m_0)$ is the payload (initial) capsule mass which is determined by $dm/dt \propto I^{1/3}$ [1]. Substituting these relations into Eq (1) and keeping terms of first order in $\langle \delta I\rangle/\langle I\rangle$, the resultant scaling has the form $\langle \delta\rho R\rangle/\langle \rho R\rangle \approx B(C_r - 1)\,\langle \delta I\rangle/\langle I\rangle$, where B is a coefficient of order 1 that depends weakly on the payload mass. This result is analogous to the BP effect for incompressible fluids, which predicts that the growth of $\delta\rho R$ is proportional to capsule convergence and in-flight shell thickening. The above discussion includes only 1D effects. 2D effects, such as lateral mass flow, can modify the convergence-driven asymmetry growth, resulting in a lower value of B for high-ℓ-number asymmetries with ratios of perturbation wavelength (λ) to in-flight shell thickness (Δ) of order one or less. To avoid this theoretical complication, we use experimental data to determine B. In addition, since initial asymmetries in capsule structure due to fabrication imperfections (with rms amplitude σ_C) should grow in the same manner during convergence, we would expect that

$$(C_r - 1)^{-2}\left(\frac{\langle \delta\rho R\rangle}{\langle \rho R\rangle}\right)^2 \approx a^2\sigma_C^2 + B^2\left(\frac{\langle \delta I\rangle}{\langle I\rangle}\right)^2, \quad (2)$$

where a is an unknown coefficient. Experimental verification of the form of this equation, and a value for B, will be found below.

Experiments were conducted on OMEGA with 60 beams of frequency-tripled (0.35 μm) UV light driving the targets directly. The total laser energy was ~23 kJ for 1-ns square pulses or ~18 kJ for shaped pulses. Individual beams were smoothed using single-color-cycle, 1 THz 2D smoothing by spectral dispersion (SSD), and polarization smoothing (PS) using birefringent wedges [5]. The room-temperature capsules had plastic (CH) shells with nominal thickness 20 μm, and were filled with 18 atm of D^3He or 15 atm of D_2 gas. Each imploded cryogenic capsules had a 80-100 μm D_2 ice layer inside a ~ 5μm CH shell [19,20]. The primary [21] or secondary protons [10] generated from D^3He reactions ($D+{}^3He \rightarrow \alpha+p$) were measured. These protons are energetic enough to easily penetrate the CH shell or D_2 ice layer, but they interact strongly enough with the capsule plasma that their energy loss is a direct measure of ρR for each spectrometer line of sight ($\rho R = \int_{E_0}^{E} \rho\left[dE/dx\right]^{-1} dE$ [22]). Because the shell (CH or D_2 ice) has lower temperature, higher density, and higher mass than the gas, the measured ρR and ρR asymmetry are dominated by ρR_{shell}.

ρR asymmetry can be seen in sample D^3He proton spectra from a single shot (25221), shown in Fig. 2. The measured mean proton energy losses $\Delta\langle E_p\rangle$ varied from 1.1 to 2.2 MeV, leading to a variation in ρR from about 35 to 70 mg/cm^2. Under current conditions a number of sources of ρR asymmetry typically contribute, with no single source dominating. When an effort is made to maintain the same capsule and laser conditions from shot to shot, the spatially-averaged $\langle \rho R\rangle$ remains relatively constant, as shown in Fig. 3. Although contiguous implosions often show similar angular variations in $\delta\rho R$ [10,11], there are small, random variations from shot to shot and a tendency for the angular variations to become uncorrelated over a long shot series.

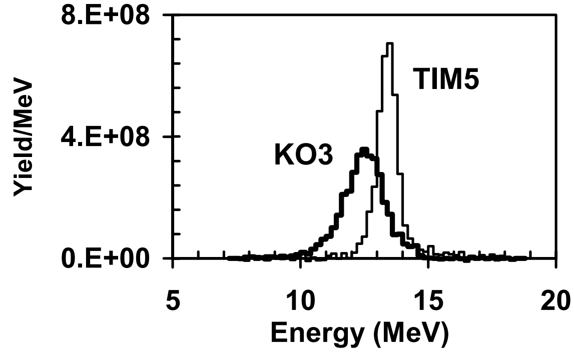

FIG. 2. Proton spectra were measured simultaneously at 7 different diagnostic ports for shot 25221. Two of the spectra are shown here, labeled with the port ID. Substantial asymmetries in the mean down-shifted energy indicate ρR asymmetry.

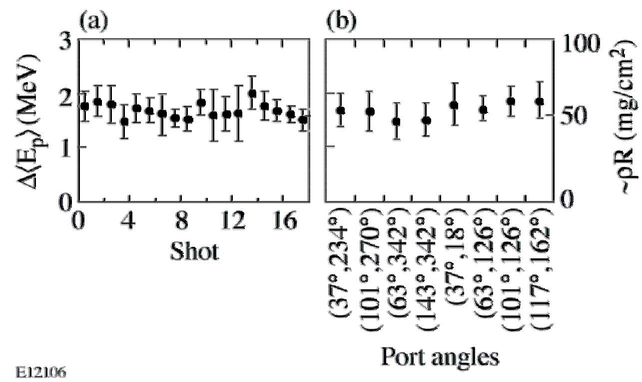

FIG. 3. (a) Measured $\Delta\langle E_p\rangle$ and inferred ρR for individual shots that were nominally identical, averaged over different port locations, plotted vs. time over a two-week time interval. (b) Measured $\Delta\langle E_p\rangle$ and inferred ρR at different port angles (θ,φ), averaged over the same shots over a two-week interval. The "error bars" are not measurement uncertainties, but standard deviations of all measurements represented by a given, plotted average.

For the shots under study here, the values of $\langle\delta\rho R\rangle/\langle\rho R\rangle$ and $\langle\delta I\rangle/\langle I\rangle$ were tabulated and are plotted in Fig. 4. The data were fit to the two-parameter function $(C_r\ -1)^{-1}\ \langle\delta\rho R\rangle/\langle\rho R\rangle = \sqrt{A^2+B^2\left(\langle\delta I\rangle/\langle I\rangle\right)^2}$; this is equivalent to Eq. (2) with $A^2 = \left\langle a^2\sigma_C^2\right\rangle$, but A^2 can also be thought of as including the average effect of any other unknown source of asymmetry not correlated with $\langle\delta I\rangle/\langle I\rangle$. As discussed in the figure caption, the data are well fit by this function using a value of $B \approx ½$, indicating that the contribution of $\langle\delta I\rangle/\langle I\rangle$ to $\langle\delta\rho R\rangle/\langle\rho R\rangle$ is

$$\frac{\langle\delta\rho R\rangle}{\langle\rho R\rangle} \approx \frac{1}{2}\left(C_r - 1\right)\frac{\langle\delta I\rangle}{\langle I\rangle}\ . \tag{3}$$

The value B = ½ in Eq. (3) was determined almost exclusively by the high-$\langle\delta I\rangle/\langle I\rangle$, high-$\langle\delta\rho R\rangle/\langle\rho R\rangle$ data points in Fig. 4. Most of these points correspond to large capsule offset, where illumination asymmetries are dominated by $\ell = 1$ and $\ell = 2$; the others correspond to cases with some laser beams turned off, where $\langle\delta I\rangle/\langle I\rangle$ was also dominated by low-ℓ structure. B may be somewhat smaller for higher modes due the effects of lateral mass flow; this will be the subject of future work. The data used here correspond to capsules with similar payload masses, but the derivation of Eq. (1) indicates that (logarithmic) dependence on payload mass should be very weak [1]. In addition, only one fill pressure was used in the room-temperature capsules (18 atm), but data from other experiments [11] with the much lower fill pressure of 4 atm are consistent with Eq. (3) (although all of these data fall in the low-$\langle\delta I\rangle/\langle I\rangle$, low-$\langle\delta\rho R\rangle/\langle\rho R\rangle$ grouping of Fig. 4). Of particular interest is the fact that Eq. (3) seems equally valid both for room-temperature, CH-shell capsules and for cryogenic capsules, even though these two types of capsules have very different theoretical susceptibilities to the RT instability [1]. The convergence-driven growth is probably more important than RT effects for the low modes under study here. (high-mode-number RT instabilities do have indirect effects on the growth of these low modes because they cause fuel-shell mix, which decreases C_r and thereby decreases the growth of $\delta\rho R$). This is particularly important for lower fill pressures, where C_r would be expected to be larger but isn't; experiments show that C_r is nearly the same for 4-atm capsules as for 18-atm capsules [23]). The data demonstrate that the growth of these low-mode asymmetries is driven primarily by convergence. Whereas different pulse shapes (adiabats), drive energies or payload masses may result in different asymmetry amplitudes, the primary differences are likely to be due to the size of C_r rather than the size of coefficient ½ in Eq. (3) or even the breakdown of the scaling itself. We conclude that the coefficient ½ in Eq. (3) may be slightly different in different ablative-drive contexts, but probably not by much.

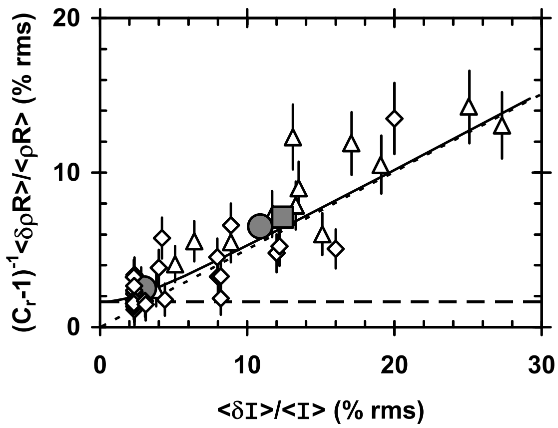

FIG. 4. Plot of $y \equiv (C_r\text{-}1)^{-1}\langle\delta\rho R\rangle/\langle\rho R\rangle$ *vs.* $x \equiv \langle\delta I\rangle/\langle I\rangle$ for the shots described in the text. The solid line represents a least-squares fit of the data to the function $y(x) = \sqrt{A^2 + B^2x^2}$, where $A = 1.63 \pm 0.33$ and $B = 0.50 \pm 0.03$; the reduced χ^2 was 1.24. The dotted line represents the contribution of $\langle\delta I\rangle/\langle I\rangle$, while the dashed line represents the mean contribution of all other sources of asymmetry. Open diamonds correspond to room-temperature capsules with plastic shells, while triangles correspond to cryogenic capsules, and it is notable that the two types of data are fairly consistent with each other. Taken separately, the plastic-shell data give $B = 0.41 \pm 0.05$ and the cryogenic data give $B = 0.55 \pm 0.04$. In most cases, values of $\langle\delta I\rangle/\langle I\rangle > 3\%$ were due to offsets of capsules from the target chamber center. Solid circles (20-μm CH shell) and square (26-μm CH shell) are from 2D simulations and show good agreement with the data and with Eq. (3).

Other evidence supports the scaling of Eq. (3). As shown in Fig. 4, it is compatible with 2D simulations for two different shell thicknesses (20 and 26 μm). This shows that the 1D arguments used to derive Eq. (3), and also the arguments given for the weak dependence on payload mass, are compatible with 2D simulations. The weak dependence on payload mass is experimentally shown through comparisons of the data shown here with recent results with 26-um-shell capsules [24], which also indicate that the scaling applies at all angles, applies for modes $\ell = 1$ and $\ell = 2$ individually, and applies at separate times during implosion.

The scaling of Eq. (3) is useful for estimating behavior in future experiments. On OMEGA, the performance of cryogenic implosions has been shown to be diminished when target offsets cause low-mode asymmetries [19,20]. Another example is cone-capsule, fast-ignition experiments on OMEGA [25], where there is no laser illumination on part of the capsule (essentially an $\ell = 1$ mode). At the NIF, the primary planned illumination scheme for indirect drive always has some low-mode-number asymmetry because of the axial hohlraum/laser geometry. Since very high values of C_r (~30-40) are required for ignition [1], Eq. (3) implies that even small amounts of drive asymmetry can disrupt implosion dynamics. Although the experimental data used in this Letter are from direct drive implosions, the scaling for indirect drive should theoretically be similar because the drive pressure scales with I in a similar way

[1]); direct experimental evidence is currently being sought in ongoing indirect-drive experiments at OMEGA [26]. Another NIF illumination scheme under consideration is polar direct drive (PDD) [27], in which laser beams arranged in an eight-ring configuration normally used for indirect-drive will be used for direct drive; although this configuration will be optimized as much as possible, it will involve significant low-mode illumination asymmetry and it is important to know how serious that will be for implosion performance. Eq. (3) can be used in these cases to estimate constraints on $\langle \delta I \rangle / \langle I \rangle$ if we know the upper limit of $\langle \delta \rho R \rangle / \langle \rho R \rangle$ that an imploded capsule can tolerate, although in some cases the criteria for ignition have been stated in terms of the symmetry of the hot, compressed core [1] rather than the symmetry of total ρR. Current work is underway to study the relationship between core symmetry and total ρR symmetry in indirect-drive implosions [26].

In summary, we have performed the first experiments to systematically study ρR asymmetries and their relationship with laser illumination asymmetries for direct-drive capsule implosions on OMEGA. A scaling law relating $\langle \delta \rho R \rangle / \langle \rho R \rangle$ to $\langle \delta I \rangle / \langle I \rangle$ has been found, and it has critical implications for future work on the National Ignition Facility (NIF) as well as OMEGA.

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