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# Effects of Nonuniform Illumination on Implosion Asymmetry in Direct-Drive Inertial Confinement Fusion

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.<sup>1–3</sup> “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<sup>1–3</sup> 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 ( $\ell > 10$ ) are primarily imprinted by nonuniformities within individual laser beams.<sup>4,5</sup> 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  $\sim 4R/\ell^2$  ( $R$  is the capsule radius); thereafter, they grow linearly.<sup>6</sup> Low-mode-number asymmetries ( $\ell \leq 10$ ) result primarily from either drive-pressure asymmetry, due to nonuniformity in on-target laser intensity, or capsule fabrication asymmetry.<sup>4,5</sup> These secular modes grow linearly throughout the entire implosion, largely due to Bell–Plesset (BP)–related convergence effects.<sup>7</sup>

A major effort has been made in current ICF research to reduce target illumination nonuniformity and capsule imperfections. Characterization of these efforts requires the measurement of any deviations from spherical symmetry in the assembled capsule mass, or areal density ( $\rho R$ ).<sup>8</sup> Previous work relied on numerical simulations to predict the conditions under which asymmetries may develop and on x-ray imaging to

provide information about emission symmetry.<sup>9</sup> Quantitative experimental information about  $\rho R$  asymmetries has not been available, however, until recent experiments<sup>10–11</sup> on OMEGA<sup>12</sup> using novel charged-particle spectrometry techniques.<sup>13</sup> These experiments have resulted in the first studies of low-mode-number  $\rho R$  asymmetries at the time of fusion burn for direct-drive spherical implosions (the diagnostic technique is sensitive to structure with mode numbers  $\ell \leq 5$ ). From these experiments we conclude that changes in laser-intensity distributions result in changes in  $\rho R$  asymmetries, while capsule imperfections do not seem to be a dominant factor under current conditions.<sup>14</sup> In this article we present new studies showing quantitatively, for the first time, how the amplitude of  $\rho R$  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)<sup>1</sup> as well as on 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  $\delta I$  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  $\sigma_b$  that tends to be in the range  $\sigma_b \leq 3\%$ .<sup>15</sup> The beams, however, overlap on the capsule surface, and the overlap reduces the net energy nonuniformity to a value  $\sigma_e$  that can be estimated from a typical measured beam profile shape and the theoretical positions of the individual beam centers:  $\sigma_e \sim 0.8\%$  to  $1.5\%$  rms. The total illumination nonuniformity on the capsule surface is higher than  $\sigma_e$  because of other contributing factors and can be estimated as  $\langle \delta I \rangle / \langle I \rangle \approx \sqrt{\sigma_e^2 + \sigma_s^2 + \sigma_p^2 + \sigma_0^2}$ . The component  $\sigma_s$ , typically  $\sim 1\%$  rms,<sup>16</sup> is due to deviations of individual beam shape profiles from that assumed in calculating  $\sigma_e$ . The component  $\sigma_p$  (typically  $\sim 1.9\%$  rms<sup>16</sup>) results from errors in the pointing of individual laser beams, and  $\sigma_0$  (typically  $\sim 1\%$  rms<sup>16</sup>) is an additional contribution from any

offset of the capsule center from the center of the target chamber ( $\sigma_0$  is  $\sim 0.2$  times the offset in  $\mu\text{m}^{16}$ ). Target offset results in drive asymmetry with strong  $\ell = 1$  and 2 modes. This is demonstrated in Fig. 98.5, which displays a two-dimensional (2-D) simulation from the hydrodynamic code *DRACO*, incorporating the measured beam imbalance and other nominal experimental conditions for an implosion with 50- $\mu\text{m}$  offset from target chamber center (TCC). The simulation indicates a strong correlation between drive asymmetry and  $\rho R$  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<sup>17</sup> because the scale length of the perturbations is typically much longer than the separation between the critical surface and the ablation surface.

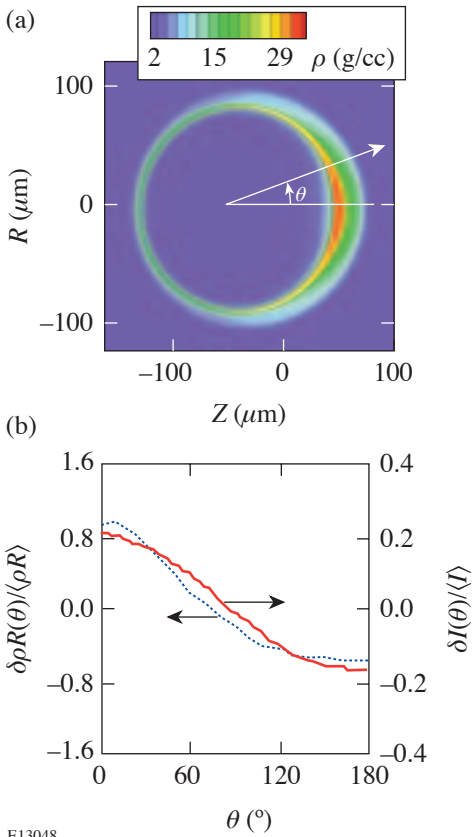


Figure 98.5

(a) Density contours at a time of peak burn ( $\sim 1.9$  ns) for an implosion of a capsule offset by 50  $\mu\text{m}$  from TCC, simulated using the 2-D 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  $\text{D}_2$  in a 20- $\mu\text{m}$  CH shell). (b) The target offset results in drive asymmetry with strong  $\ell = 1$  and 2 modes, which generates a correlated  $\rho R$  asymmetry.

The amplitude of asymmetries in  $\rho R$  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  $\rho R$  asymmetries relate to  $\langle \delta I \rangle / \langle I \rangle$  can be derived from considerations of implosion dynamics, assuming that  $\rho R$  asymmetries are seeded by the illumination asymmetries and modified due to effects of capsule convergence. The growth rates of low- $\ell$ -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  $\langle \delta g \rangle / \langle g \rangle \approx \langle \delta V_{\text{imp}} \rangle / \langle V_{\text{imp}} \rangle$  (Ref. 1), where  $V_{\text{imp}} = V_{\text{imp}}(t)$  is the capsule implosion velocity. Starting with  $(R_0 - R) \approx V_{\text{imp}} t_{\text{imp}}$  and considering implosion dynamics, one obtains

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

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  $\rho_0$  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 “burnthrough” experiments<sup>18</sup>). One obtains  $-\langle \delta R \rangle / \langle R \rangle \approx 1/2 \langle \delta \rho R \rangle / \langle \rho R \rangle$ .  $V_{\text{imp}}$  is a function of laser intensity on target for direct-drive implosions with

$$V_{\text{imp}} \propto I^{1/3} \ln(m_0/m),$$

where  $m(m_0)$  is the payload (initial) capsule mass determined by  $dm/dt \propto I^\alpha$  ( $\alpha$  is a constant).<sup>1,19,20</sup> 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 the order of 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 1-D effects.

Two-dimensional (2-D) effects, such as lateral mass flow, can modify the convergence-driven asymmetry growth, resulting in a lower value of  $B$  for high- $\ell$ -number asymmetries with ratios of perturbation wavelength ( $\lambda$ ) to in-flight shell thickness ( $\Delta$ ) of the order of 1 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  $\sigma_C$ ) 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- $\mu\text{m}$ ) UV light driving the targets directly. The total laser energy was  $\sim 23$  kJ for 1-ns square pulses or  $\sim 18$  kJ for shaped pulses. Individual beams were smoothed using single-color-cycle, 1-THz, 2-D smoothing by spectral dispersion (SSD) and polarization smoothing (PS) using birefringent wedges.<sup>5</sup> The room-temperature capsules had plastic (CH) shells with 20- $\mu\text{m}$  nominal thickness and were filled with 18 atm of  $\text{D}^3\text{He}$  or 15 atm of  $\text{D}_2$  gas. Each imploded cryogenic capsule had an 80- to 100- $\mu\text{m}$   $\text{D}_2$ -ice layer inside an  $\sim 5$ - $\mu\text{m}$  CH shell.<sup>21,22</sup> The primary<sup>23</sup> or secondary protons<sup>10</sup> generated from  $\text{D}^3\text{He}$  reactions ( $\text{D} + ^3\text{He} \rightarrow \alpha + p$ ) were measured. These protons are energetic enough to easily penetrate the CH shell or  $\text{D}_2$ -ice layer, but they interact strongly enough with the capsule plasma that their energy loss is a direct measure of  $\rho R$  for each spectrometer line of sight:

$$\rho R = \int_{E_0}^E \rho(dE/dx)^{-1} dE$$

[see (Ref. 24)]. Because the shell (CH or  $\text{D}_2$  ice) has a lower temperature, higher density, and higher mass than the gas, the measured  $\rho R$  and  $\rho R$  asymmetry are dominated by  $\rho R_{\text{shell}}$ .

$\rho R$  asymmetry can be seen in sample  $\text{D}^3\text{He}$  proton spectra from a single shot (25221), shown in Fig. 98.6. The measured mean proton energy losses  $\Delta\langle E_p \rangle$  varied from 1.1 to 2.2 MeV, leading to a variation in  $\rho R$  from about 35 to 70  $\text{mg}/\text{cm}^2$ . Under current conditions a number of sources of  $\rho R$  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. 98.7. Although contiguous implosions often show similar angular variations in  $\delta\rho R$ ,<sup>10,11</sup> there are small, random variations from shot to shot and a tendency for the angular variations to become uncorrelated over a long shot series.

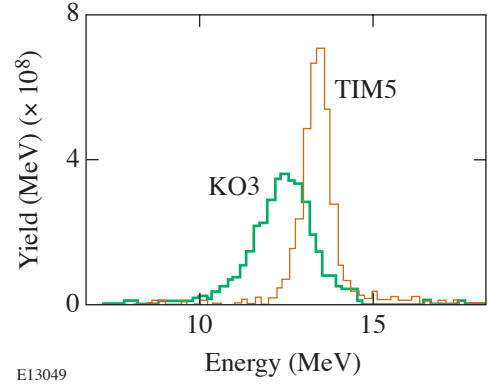


Figure 98.6

Proton spectra were measured simultaneously at seven different diagnostic ports for shot 25221. Two of the spectra are shown here, labeled with the port ID. Substantial asymmetries in the mean downshifted energy indicate  $\rho R$  asymmetry.

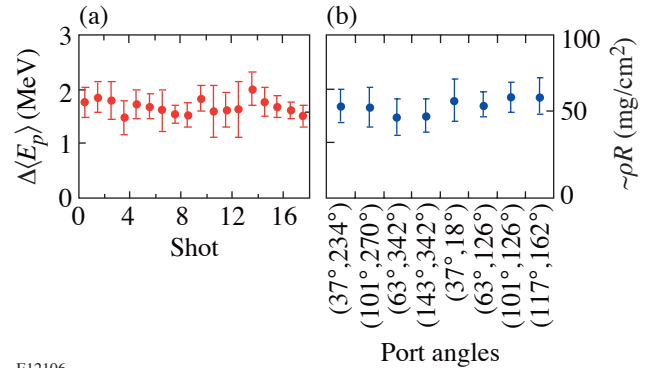


Figure 98.7

(a) Measured  $\Delta\langle E_p \rangle$  and inferred  $\rho R$  for individual shots that were nominally identical, averaged over different port locations, plotted versus time over a two-week time interval. (b) Measured  $\Delta\langle E_p \rangle$  and inferred  $\rho R$  at different port angles ( $\theta, \varphi$ ), 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. 98.8. The data were fit to the two-parameter function

$$(C_r - 1)^{-1} \langle\delta\rho R\rangle/\langle\rho R\rangle = \sqrt{A^2 + B^2(\langle\delta I\rangle/\langle I\rangle)^2};$$

this is equivalent to Eq. (2) with  $A^2 = \langle a^2 \sigma_C^2 \rangle$ , 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  $B \approx 1/2$ , indicating that the contribution of  $\langle\delta I\rangle/\langle I\rangle$  to  $\langle\delta\rho R\rangle/\langle\rho R\rangle$  is

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

The value  $B = 1/2$  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. 98.8. 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- $\ell$  structure.  $B$  may be somewhat smaller for higher modes due to 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. (2) indicates that (logarithmic) dependence on payload mass should be very weak.<sup>1</sup> In addition, only one fill pressure was used in the room-temperature capsules (18 atm), but data from other experiments<sup>11</sup> 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. 98.8). Of particular interest is the fact that Eq. (3) seems equally valid for both room-temperature, CH-shell capsules and cryogenic capsules, even though these two types of capsules have very different theoretical susceptibilities to the RT instability.<sup>1</sup> 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 is not; experiments show that  $C_r$  is nearly the same for 4-atm capsules as for 18-atm capsules.<sup>25</sup> 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 the coefficient 1/2 in Eq. (3) or even the breakdown of the scaling itself. We conclude that the coefficient 1/2 in Eq. (3) may be slightly different in different ablative-drive contexts, but probably not by much.

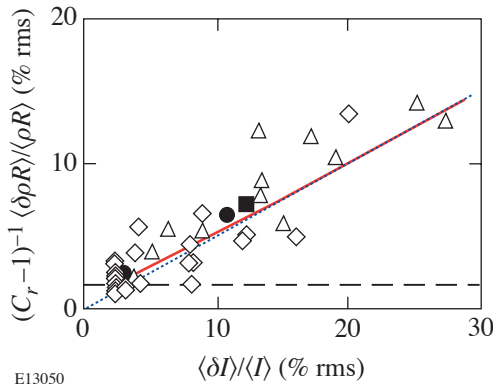


Figure 98.8

Plot of  $y = (C_r - 1)^{-1} \langle\delta\rho R\rangle/\langle\rho R\rangle$  versus  $x = \langle\delta I\rangle/\langle I\rangle$  for the shots described in the text. The solid line represents a least-squares fit of the data to the function  $y(x) = \sqrt{A^2 + B^2 x^2}$ , where  $A = 1.63 \pm 0.33$  and  $B = 0.50 \pm 0.03$ ; the reduced  $\chi^2$  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; 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- $\mu\text{m}$  CH shell) and a solid square (26- $\mu\text{m}$  CH shell) are from 2-D simulations and show good agreement with the data and with Eq. (3).

Other evidence supports the scaling of Eq. (3). As shown in Fig. 98.8, it is compatible with 2-D simulations for two different shell thicknesses (20 and 26  $\mu\text{m}$ ). This shows that the 1-D arguments used to derive Eq. (3), and also the arguments given for the weak dependence on payload mass, are compatible with 2-D simulations. The weak dependence on payload mass is experimentally shown through comparisons of the data shown here with recent results with 26- $\mu\text{m}$ -shell capsules,<sup>26</sup> which also indicates that the scaling applies at all angles, applies for modes  $\ell = 1$  and  $\ell = 2$  individually, and applies at separate times during the 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.<sup>21,22</sup> Another example is

cone-capsule, fast-ignition experiments on OMEGA,<sup>27</sup> where there is no laser illumination on part of the capsule (essentially an  $\ell = 1$  mode). For future indirect-drive experiments at the NIF, low-mode symmetry is an important design issue.<sup>1</sup> Since very high values of  $C_r$  ( $\sim 30$  to  $40$ ) are required for ignition,<sup>1</sup> Eq. (3) implies that even small amounts of drive asymmetry can disrupt implosion dynamics. Although the experimental data used in this article 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;<sup>1</sup> direct experimental evidence is currently being sought in ongoing indirect-drive experiments at OMEGA.<sup>28</sup> Another NIF illumination scheme under consideration is polar direct drive (PDD),<sup>29</sup> in which laser beams arranged in a six-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. Equation (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<sup>1</sup> rather than the symmetry of total  $\rho R$ . Current work is underway to study the relationship between core symmetry and total  $\rho R$  symmetry in indirect-drive implosions.<sup>28</sup>

In summary, we have performed the first experiments to systematically study  $\rho R$  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 on OMEGA.

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14. This is because there is often a great deal of similarity in the asymmetries of contiguous shots, while capsule imperfections would be expected to vary randomly from shot to shot.
15. We have ignored the fact that the individual laser beams may have slightly different time histories, resulting in a small time-dependent power imbalance, as discussed in Ref. 5.

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