Demonstrating ignition hydrodynamic equivalence in direct-drive cryogenic implosions on OMEGA

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Abstract. Achieving ignition in a direct-drive cryogenic implosion at the National Ignition Facility (NIF) requires reaching central stagnation pressures in excess of 100 Gbar, which is a factor of 3 to 4 less than what is required for indirect-drive designs. The OMEGA Laser System is used to study the physics of cryogenic implosions that are hydrodynamically equivalent to the spherical ignition designs of the NIF. Current cryogenic implosions on OMEGA have reached 56 Gbar, and implosions with shell convergence CR < 17 and fuel adiabat α > 3.5 proceed close to 1-D predictions. Demonstrating hydrodynamic equivalence on OMEGA will require reducing coupling losses caused by cross-beam energy transfer (CBET), minimizing long-wavelength nonuniformity seeded by power imbalance and target offset, and removing target debris accumulated during cryogenic target production.

1. INTRODUCTION

The main approach to ignition by means of laser-driven inertial confinement fusion [1] (ICF) currently pursued by the National Ignition Facility [2] (NIF) is x-ray (or indirect) drive. In the other ICF laser approach, direct drive, the target is driven by laser irradiation directly coupled to the plasma blowing off the imploding capsule. The main advantage of the indirect-drive approach is reduced sensitivity of drive uniformity to short-scale beam nonuniformities. The main advantage of direct drive is higher coupling efficiency (by a factor of 3 to 5) of the laser energy into kinetic energy of the shell (hydrodynamic efficiency) compared to that of x-ray drive. The OMEGA Laser System [3] and the KrF laser NIKE at the Naval Research laboratory [4] have been the principal facilities for direct-drive experiments in the United States. Early challenges in achieving beam uniformity required for ignition have been resolved over the last several decades by introducing several beam smoothing techniques. These include distributed...
Compared to the x-ray drive, direct-drive targets couple a larger fraction of laser energy into shell kinetic energy and internal energy of the neutron-producing central region of the target (hot spot) at peak fuel compression. This relaxes the requirement on shell convergence and hot-spot pressure in an igniting target. This can be shown with the help of a commonly used ignition condition (which can also be derived from generalized Lawson criterion [12]) according to which plasma self-heating is initiated by $pdV$ work of the shell and alpha heating if the product of areal density and ion temperature inside the shot spot satisfies $[1, 13]$  

$$\left(\rho R\right)_{hs} \times T \gtrsim 0.3 \text{ g/cm}^2 \times 5 \text{ keV},$$  

(1)

where $\rho$, $R_{hs}$, and $T$ are the hot-spot density, radius, and temperature. Substituting expressions for the pressure $p_{hs} = (1 + Z)\rho T/m_i$ ($Z$ is the average ion charge and $m_i$ is the average ion mass) and internal energy $E_{hs} = 3/2 p_{hs} V_{hs}$ ($V_{hs}$ is the neutron-averaged hot-spot volume) into Eq. (1) gives a minimum pressure requirement (threshold) for ignition,

$$p_{hs} > p_{thr} = 250 \text{ Gbar } \left(\frac{E_{hs}}{10 \text{ kJ}}\right)^{-1/2}, \text{ or } \bar{P} = \frac{p_{hs}}{p_{thr}} = \left(\frac{p_{hs}}{250 \text{ Gbar}}\right) \sqrt{\frac{E_{hs}}{10 \text{ kJ}}} > 1,$$

(2)

where $\bar{P}$ is the ignition pressure parameter.

The dependence of the threshold pressure $p_{thr}$ on the hot-spot internal energy is shown in Fig. 1. Spherically symmetric direct-drive cryogenic designs on OMEGA couple up to 0.44 kJ (out of 26-kJ incident laser energy) into the hot-spot internal energy. When hydrodynamically scaled to the NIF-size laser energy (1.5 MJ to 1.8 MJ), these designs are predicted to couple 5× to 10× more energy into the hot spot [25 kJ to 40 kJ, depending on laser coupling efficiency (see red-shaded region in Fig. 1)] compared to that of indirect drive [4 kJ to 5 kJ (see blue-shaded region in Fig. 1)], resulting in 2.5× to 3× lower hot-spot pressures required for ignition. The hot-spot size also gets larger with $E_{hs}$, leading to smaller shell convergence ($Cr \sim 22$ compared to 35 to 40 in present x-ray-drive ignition designs) and less-demanding long-wavelength drive uniformity requirements.
2. OMEGA cryogenic implosions

To separate one-dimensional (1-D) factors that limit the target performance (drive efficiency, adiabat, etc.) from three-dimensional (3-D) effects, dedicated experiments are performed on OMEGA with the purpose of improving physics understanding and accuracy of 1-D code predictions. To identify critical implosion parameters, the 1-D scaling laws for peak pressure, hot-spot energy, and the ignition pressure parameter are written in terms of implosion velocity predictions. To identify critical implosion parameters, the 1-D scaling laws for peak pressure, hot-spot energy, and the ignition pressure parameter are written in terms of implosion velocity \( v_{imp} \) (defined as the peak mass-averaged shell velocity), the drive (ablation) pressure \( p_a \), and the in-flight shell adiabat \( \alpha \) (ratio of the shell pressure to Fermi pressure at shell density) [14]:

\[
p_{hs}^{1-D} \sim \frac{p_d^{1/3} v_{imp}^{10/3}}{\alpha}, \quad E_{hs}^{1-D} \sim E_{kin} \frac{v_{imp}^{4/3}}{\alpha^{2/5} p_d^{4/15}}, \quad \bar{P}_{1-D} \sim \frac{\sqrt{E_{kin} v_{imp}^{4/5}} p_d^{1/5}}{\alpha^{6/5}}. \tag{3}
\]

The implosion velocity and shell kinetic energy are inferred in an experiment by measuring ablation-front trajectory and mass ablation rate using self-emission imaging [15]. The ablation pressure is inferred from simulations that match the measured ablation-front trajectory, mass ablation rate, bang time [16], and scattered-light power and spectrum [17]. Finally, the shock-induced adiabat is inferred by measuring shock velocities early in the pulse using VISAR [18]. An additional fuel-adiabat increase caused by hot-electron preheat is estimated by measuring the hard x-ray signal [19] and areal density [20, 21] in mid- to high-adiabat implosions (the areal density in 1-D, for a given laser energy, depends mainly on shell adiabat [22], \( \rho R \sim \alpha^{-0.5} \)). A detailed comparison of 1-D simulation results using the hydrocode LILAC [23] with the data [14] shows good agreement between the two for a variety of target designs and drive conditions. One-dimensional simulations include nonlocal thermal transport model [24], a ray-based cross beam energy transfer (CBET) model [25], and first-principle EOS (FPEOS) models [26] for both the DT ice and CD ablator.

An analysis of direct-drive implosions on OMEGA has shown that coupling losses related to CBET [25] significantly limit the ablation pressure (as much as 40% on OMEGA and up to 60% on the NIF-scale targets), implosion velocity, and shell kinetic energy. Considering such losses, demonstrating the hydrodynamic equivalence of implosions on OMEGA to ignition designs on the NIF requires the shell IFAR to exceed the current stability threshold level (∼ 22) [14]. One of the CBET mitigation strategies [27] involves using laser illumination with a laser beam diameter that is smaller than the initial shell diameter. This strategy, as demonstrated both theoretically and experimentally, recovers some coupling losses and increases the ablation pressure. Since the effect of CBET is small early in the implosion when the density scalelength and laser intensity are small, beam zooming schemes [28] consider the beam focal spot at an early time to be at the initial target radius (to maximize the illumination uniformity), reducing it to 0.6× to 0.7× of that size at the beginning of the main drive.

While zooming implementation on OMEGA is still a few years away, a test of the CBET reduction strategy was performed using “static” DPP’s that produce the focal spots smaller than the initial target size through the entire drive pulse. The focal-spot radius (defined as the radius of a 95% beam energy contour) in these experiments was fixed at \( R_b = 410 \) μm. The ratio of \( R_b \) to target size \( (R_{target}) \) was changed by varying the \( R_{target} \) from 400 μm to 500 μm. SSD was off during the main pulse for larger targets with \( R_{target} = 450 \) μm, 480 μm, and 500 μm (to increase on-target laser energy), while the targets with \( R_{target} = 400 \) μm, 430 μm, and 450 μm used SSD for the entire pulse. Hence, the ratio \( R_b/R_{target} \) changed from 1.025 to 0.78. According to simulation results (which matched the observables), the smallest target \( (R_{target} = 400 \) μm) had \( v_{imp} = 3.5 \) to \( 3.6 \times 10^7 \) cm/s and a hydroefficiency of \( f_{hydro} = 3.5\% \), while the largest target had similar implosion velocity \( v_{imp} = 3.6 \) to \( 3.7 \times 10^7 \) cm/s, but more than twice larger hydroefficiency \( f_{hydro} = 7.2\% \). Such an increase in hydroefficiency was partially caused by smaller refraction losses experienced by the larger target (smaller \( R_b/R_{target} \) and
Figure 2. (a) Hot-spot pressure, inferred from experimental observables, as a function of target size. (b) Inferred hot-spot pressure normalized to 1-D code predictions versus the predicted shell convergence at 1-D bang time. The vertical lines on both plots show a typical experimental error bar.

larger density scale length) and partially by reduced CBET losses. To quantify each effect, a simulation was performed with $R_{\text{target}} = 500 \, \mu m$, where the $R_b$ was increased to match $R_{\text{target}}$ and the laser energy was increased from 27.5 kJ (used in an experiment) to 32 kJ to avoid coasting chase. In such a simulation, implosion velocity was dropped by 11% to $v_{\text{imp}} = 3.2 \times 10^7$ cm/s and the shell hydroefficiency was reduced by 26% to $f_{\text{hydro}} = 5.3\%$.

Figure 2 shows the target performance ($p_{hs}$) for different target diameters. The hot-spot pressure is inferred [29] by using the measured neutron yield, burn duration $\Delta T_{\text{burn}}$ [using both the neutron temporal diagnostics (NTD) [16] and framing-camera measurement of the x-ray–pressure is inferred [29] by using the measured neutron yield, burn duration $\Delta T_{\text{burn}}$ and the laser energy was increased from 27.5 kJ (used in an experiment) to 32 kJ to avoid coasting chase. In such a simulation, implosion velocity was dropped by 11% to $v_{\text{imp}} = 3.2 \times 10^7$ cm/s and the shell hydroefficiency was reduced by 26% to $f_{\text{hydro}} = 5.3\%$.

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energy of the hot spot. To account for the first effect (early pressure sampling), Fig. 4 plots the inferred hot-spot pressure normalized to the predicted pressure at the measured (earlier) bang time as a function of 1-D shell convergence calculated at the experimental bang time. Figure 4 shows that implosions with a fuel adiabat of $\alpha > 3.5$ proceed close to 1-D predictions up to a shell convergence of $C_r \sim 17$. An additional shell convergence does not lead to an increased $pdV$ work on the hot-spot because of the RT growth of low-$l$ modes. Further reduction in the target performance at lower fuel adiabat is caused by compromised shell integrity due to short-wavelength nonuniformity growth during shell acceleration seeded by shell imperfections (mainly target debris).

In summary, the cryogenic campaign with reduced beam size relative to the target size ($R_b/R_{\text{target}} < 1$), performed on OMEGA to reduce CBET losses, demonstrated increased laser coupling and hydrodynamic efficiency. This coupling enhancement, however, did not improve the target performance. Numerical simulations indicate that long-wavelength nonuniformities caused by target offset and power imbalance lead to an increased target central volume and early burn truncation. This effect is exacerbated by a reduction in beam overlap when the target size is increased relative to beam size.

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