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Demonstration of the Highest Deuterium-Tritium Areal Density Using Multiple-Picket Cryogenic Designs on OMEGA


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The performance of triple-picket deuterium-tritium cryogenic target designs on the OMEGA Laser System [T. R. Boehly et al., Opt. Commun. 133, 495 (1997)] is reported. These designs facilitate control of shock heating in low-adiabat inertial confinement fusion targets. Areal densities up to 300 mg/cm² (the highest ever measured in cryogenic deuterium-tritium implosions) are inferred in the experiments with an implosion velocity \( \sim 3 \times 10^7 \) cm/s driven at peak laser intensities of \( 8 \times 10^{14} \) W/cm². Extension of these designs to ignition on the National Ignition Facility [J. A. Paisner et al., Laser Focus World 30, 75 (1994)] is presented.

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In inertial confinement fusion implosions a cryogenic shell of deuterium-tritium (DT) fuel is driven inward by means of direct or indirect laser illumination to achieve high compression and burn [1]. Fuel burn proceeds in two stages. First, a lower-density, higher-temperature (\( \sim 10 \) keV) hot spot is formed by compression (PdV) work provided by higher-density, lower-temperature shell. Calculations show that to initiate burn, shell kinetic energy must exceed the threshold value [2], which depends on the shell implosion velocity \( V_{imp} \) (peak mass-averaged shell velocity), the in-flight shell adiabat \( \alpha_{if} \) (ratio of shell pressure to the Fermi-degenerate pressure at the peak shell density), and the drive pressure \( p_d \). Second, as burn propagates through the fuel, shell inertia provides confinement time sufficient to burn a significant fraction of the assembled fuel. This requires fuel areal densities \( \langle \rho R \rangle \) at peak compression in excess of \( \sim 0.9 \) g/cm² [1]. The peak areal density in a direct-drive implosion depends on \( \alpha_{if} \) and laser energy \( E_L \) [3]:

\[
\text{max}(\rho R)_g/cm^2 = 2.6 \frac{E_{L, MJ}^{1/3}}{\alpha_{if}^{2/3}}.
\]

Subscript MJ refers to megajoule energy units. To burn a sufficient fraction of fuel, the shell adiabat must be \( \alpha_{if} \leq 7E_{L, MJ}^{0.6} \). While burn initiation physics requires laser energy in excess of \( \sim 300 \) kJ, which will be available on the National Ignition Facility (NIF) [4], implosions on the OMEGA laser [5] validate the ability of ignition designs to assemble cryogenic fuel with ignition-relevant implosion velocities \( (V_{imp} > 3 \times 10^7 \) cm/s), maintaining the required fuel adiabat. A deviation of the adiabat from the designed value can be inferred by comparing the measured and predicted values of \( \rho R \). The areal density is determined by measuring spectral shapes of reaction products as they interact with the fuel [6,7]. This gives a value \( \langle \rho R \rangle_n \) averaged over reaction time history. \( \langle \rho R \rangle_n \) is calculated by using Eq. (1) with a numerical factor of 1.7 instead of 2.6 [3]. Then, an OMEGA cryogenic DT design, hydrodynamically equivalent to an \( \alpha_{if} = 2 \) ignition design on the NIF, is predicted to achieve \( \langle \rho R \rangle_n \sim 300 \) mg/cm² at a laser energy of 30 kJ and a laser absorption fraction of \( \sim 70\% \), typical for OMEGA-scale targets. Reaching these areal densities on OMEGA, therefore, is a crucial step in validating predictive capabilities of hydrodynamic codes used to design ignition targets on the NIF.

The shell adiabat is determined by heating sources, including shock waves, radiation, and suprathermal electrons. Because of inaccuracies in the models used in target designing, experimental tuning is required to ensure that preheat is at an acceptable level. This Letter describes direct-drive target designs optimized for experimental shock timing to prevent adiabat degradation caused by excessive shock heating. This is accomplished by combining three intensity pickets with the main drive pulse [triple-picket (TP) design]. The main pulse in this case requires minimal shaping. Areal densities up to 300 mg/cm² are observed in cryogenic DT implosions on OMEGA using the TP designs driven at peak intensities \( \sim 8 \times 10^{14} \) W/cm².

One of the main challenges in designing hot-spot ignition implosions is to control the generation of strong shocks while accelerating the fuel shell to \( V_{imp} > 3 \times 10^7 \) cm/s. To avoid excessive shock heating, only few-Mbar shocks can be launched into cryogenic fuel at the beginning of an implosion. Preventing shell disruption due to the Rayleigh-Taylor instability [8], on the other hand, requires drive pressures \( p_d \) in excess of 100 Mbar since the...
shell’s in-flight aspect ratio \( A_{in} \) (ratio of shell radius \( R \) to shell thickness) is proportional to \( p_d^{2/5} \) [3] and shells with higher \( A_{in} \) are more susceptible to the perturbation growth during the acceleration phase. Pressure increase from a few Mbar to 100 Mbar can be achieved either adiabatically [continuous-pulse (CP) design] [9,10] or by launching a sequence of shocks of increasing strength [multiple-shock (MS) designs] [1,11].

Early cryogenic spherical implosions on OMEGA used the CP designs [12–15]. Both 5- and 10-\( \mu \)m-thick deuterated plastic (CD) shells with cryogenic 95-\( \mu \)m-thick D\(_2\) and 80-\( \mu \)m-thick DT layers were used in these experiments. Areal densities close to the predicted values \((\rho R)_n \sim 130 \text{ mg/cm}^2\) were achieved in implosions with 5 \( \mu \)m shells driven at peak intensities below \( I_{lim} \approx 3 \times 10^{14} \text{ W/cm}^2 \) \((p_d \sim 50 \text{ Mbar})\) and a laser pulse contrast ratio (CR) of less than 3.5. When 10 \( \mu \)m shells were used, \((\rho R)_n \sim 200 \text{ mg/cm}^2\) \((80\%-90\% \text{ of the predicted values})\) were measured for designs with \( I_{lim} \approx 5 \times 10^{14} \text{ W/cm}^2 \) \((p_d \sim 75 \text{ Mbar})\) and CR < 30 [15]. The implosion velocity was \( V_{imp} \approx 2.2 \times 10^7 \text{ cm/s}\). Increasing drive intensities above \( I_{lim} \) resulted in significant deviations of measured and predicted \((\rho R)_n\) [14]. Shock velocity measured in the CP designs using velocity interferometry system for any reflector (VISAR) [16] revealed difficulty in reproducing an adiabatic compression wave predicted in simulations [14,17]. Since the effect of steepening a compression wave into a shock, not predicted in simulations, is exacerbated by increasing either peak drive intensity or laser pulse CR, it is impractical to experimentally tune the adiabat in the CP designs to ignition-relevant values.

Initial fuel compression prior to reaching peak drive intensity can be accurately controlled in the MS designs by launching a sequence of shocks using intensity pickets. Next, we describe the main features of such designs. First, we assume that \( N \) shocks are launched by narrow intensity pickets, and the main shock is launched and supported by the main pulse. Since pressure of an unsupported shock can be neglected with respect to post-shock velocity \((\text{PdV work on a fluid})\), pressure increase from a few Mbar to 100 Mbar can be achieved either adiabatically or by launching a sequence of shocks of increasing strength [multiple-shock (MS) designs] [1,11].

Next, a simple model is used to gain insight into the shock evolution in a multiple-picket design. A shock wave traveling along the \( x \) axis with a velocity \( U_{sh} \) is assumed to be sufficiently strong so that the flow velocity ahead of the shock can be neglected with respect to post-shock velocity in the laboratory frame of reference. Gradients in the flow created by unsupported shocks lead to \( \text{PdV work on a fluid element} \), \( d_p \equiv \partial \rho \partial v \equiv -(5/3) \rho \rho_{sh} \). The spatial gradient in velocity can be expressed in terms of pressure gradient and acceleration in the shock-front frame using Bernoulli’s relation, \( \partial \rho \partial v + \partial \rho \partial p / \rho = -\partial U_{sh} \). In the strong-shock limit, \( \rho = 0\), and \( U_{sh} = \sqrt{(2/3)p_0/\rho_0} \), leading to \( d_p = -U_{sh}^6 \partial \rho / \rho \). This equation can be simplified by introducing mass coordinate, \( dm = \rho dx \), and replacing time with the mass \( m_s \) overtaken by the shock, \( dm_s = \rho U_{sh} dt \). At the shock front, this gives

\[
\frac{d \ln(p_U^{2/3})}{dm_s} = -4 \left( \frac{\partial \ln p}{\partial m} \right)_{s}.
\]

According to a self-similar solution [19] and simulation results, the pressure behind the unsupported shock changes nearly linearly with mass, leading to solution of Eq. (3) in the form \( p_U \sim m_s^{-1.14} \rho_0^{0.71} \). The first shock travels through uniform density, and its pressure decays as \( p_1 \sim m_s^{-1.14} \). The post-shock adiabat varies as \( \alpha_1 \sim m_s^{-1.14} \). Compared
to the results of self-similar solution [19], the error in the
power index predicted by this model is within 10%. The
density after the shock evolves as \( \rho \sim (p/\alpha_i)^{3/5} \). Thus, the
density ahead of the second-shock front grows as \( \rho_0 \sim m_1^{1.29} \),
and shock pressure decays as \( p_2 \sim m_2^{-0.22} \). To generalize,
if an \( i + 1 \) shock with \( p_{i+1} \sim m_3^{\delta_{i+1}} \) travels through
the flow with an adiabat profile \( \alpha_i \sim m^{-\omega_i} \), the model gives
\( \delta_{i+1} = 0.57 \delta_i + 0.43 \) and \( \omega_{i+1} = 0.57 \omega_i + 1.71 \) with
\( \delta_1 = - \omega_1 = -1.14 \). This shows that starting with the
third shock, the pressure at the unsupported shock front
increases as the shock travels through the shell. For the
main shock (launched after \( N \) decaying shocks from the
pickets) supported by pressure \( p_d \), Eq. (3) gives (assuming
again \( p \sim m \))
\[
\rho_{\text{main}} = p_d \left[ 3(\omega_N + 1)(m_\omega/m_\rho)^{\delta_N} - 8 \right]/(3\omega_N - 5),
\]
where \( m_\rho \) is a normalization constant which depends on picket duration.

The model shows that the main shock pressure increases
as the shock propagates through the shell, significantly
exceeding the ablation pressure. To avoid an increase in
\( \alpha_{\text{max}} \) due to this pressure amplification, it is necessary to
either increase the number of pickets to 4 or reduce the
strength of the main shock by introducing an intensity step,
at the beginning of the main drive. Because of short time
separation between the last picket and the main drive in a
quadruple-picket design, a combination of three pickets
and a step pulse is chosen as a baseline for the multiple-
picket, low-adiabat designs.

As described earlier, all shocks launched by the pickets
and the main drive must coalesce nearly simultaneously.
Leading shock velocity in this case decays prior to coalescence
time at which the velocity experiences a sequence of
3 jumps up to \( V_{\text{shock}} > 120 \) \( \mu \)m/ns. Time separation be-
tween each jump in an OMEGA design is less than 50 ps.
The measured velocity, therefore, is expected to increase
continuously, as shown in Fig. 1 (dotted line). Because of
the radiative precursor, the VISAR signal is absorbed in a
region ahead of the shock front if \( V_{\text{shock}} > 75 \) \( \mu \)m/ns [20].

Thus, only the first shock velocity and time of the coalescence
sequence can be measured by the VISAR in an
optimized design. Deviations from the optimal strength
of any particular shock would result in early catch up of
two shocks and lead to multiple velocity jumps, well
separated in time and resolved by the VISAR measurement.
For example, if the third picket is too high, the third
shock will prematurely overtake the second and first
shocks, resulting in a velocity jump up to 70 \( \mu \)m/ns. This is shown in
Fig. 1 (dashed line) where two coalescence events are separated by 300 ps. Note that premature coalescence of the second and first shocks would lead to a
smaller velocity jump (\( \sim 50 \) \( \mu \)m/ns). Also shown in
Fig. 1 is the result of VISAR measurement (solid line) which is in very good agreement with the predictions
calculated using the one-dimensional hydrocode LILAC
[21]. These experiments were performed on OMEGA
with a 900-\( \mu \)m-diameter, 10-\( \mu \)m-thick CD shell filled
with liquid D\(_2\) and fitted with a VISAR cone [17].

To verify the shock optimization procedure and validate
control of the main shock strength with an intensity step,
the TP designs with both square- and a step-main pulses
were used on the OMEGA Laser System to drive targets
with a 65-\( \mu \)m-thick cryogenic DT layer overcoated with a
10-\( \mu \)m CD shell. The pulse shapes shown in Fig. 2 had a
peak intensity of \( 8 \times 10^{14} \) W/cm\(^2\). The laser energy varied
from 23 kJ for the square-main pulse to 25 kJ for the step-
main pulse, respectively. The predicted implosion velocity
in these designs reached \( 3 \times 10^{7} \) cm/s. A magnetic recoil
spectrometer (MRS) [6] was used to infer \( \langle \rho R \rangle_h \). Two
charged-particle spectrometers were also used to measure
the spectral shape of knock-on deuterons, elastically scattered
by primary DT neutrons. The shape in the knock-on
deuteron spectrum is insensitive, however, to areal den-
sities above \( \langle \rho R \rangle_h > 180 \) mg/cm\(^2\) [6]. These measurements
were used to infer the lower limit on \( \langle \rho R \rangle_h \) as well

![FIG. 1. Example of leading shock velocity history measured (thick solid line) and predicted (dashed line) in the TP design with a mistimed third shock. The calculated velocity history for an optimized design is shown by a dotted line.](image1)

![FIG. 2. Predicted and measured areal densities for triple-picket square (circles) and step (squares) OMEGA designs. The inserts show the pulse shapes used to drive the implosions.](image2)
as assess asymmetries developed at different views of an implosion. In Fig. 2 the measured areal densities are compared to those calculated using LILAC. Good agreement between measurements and calculations validates the accuracy of shock tuning in the TP designs. Also, the observed increase in $\rho V$ in the step design confirms that the inner adiabat can be accurately controlled by changing step amplitude in the main drive.

Based on the good performance of the TP designs on OMEGA, a new direct-drive-ignition design is proposed for the NIF (Fig. 3). Driven at a peak intensity of $8 \times 10^{14} \text{W/cm}^2$, the shell reaches $V_{\text{imp}} = (3.5-4) \times 10^7 \text{cm/s}$, depending on the thickness of the fuel layer. At a laser energy of 1.5 MJ this design is predicted to ignite with a gain $G = 48$. The stability assessment of the NIF TP design is currently in progress.

In summary, triple-picket designs were used in cryogenic DT implosions on OMEGA. The highest areal densities ever measured in cryogenic DT implosions (up to 300 mg/cm$^2$) were inferred with $V_{\text{imp}} \sim 3 \times 10^7 \text{cm/s}$ driven at a peak laser intensity of $8 \times 10^{14} \text{W/cm}^2$. Scaled to the NIF, the TP design is predicted to ignite with a gain $G = 48$.

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