Inertial Fusion Energy Target Designs with Advanced Laser Technologies

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Executive Summary – The proposed work is focused on developing advanced designs for inertial fusion energy (IFE) applications. The innovative approach is based on three key elements: (1) **new broadband and deep UV laser technologies** to mitigate deleterious effects of laser-plasma interaction; (2) **high-gain (G > 100) laser direct-drive (LDD) designs** with enhanced laser coupling and mitigated imprint at moderate laser energies ($E_L \sim 1$ MJ); and (3) **simplicity and low-cost of targets** [relative to nominal deuterium−tritium (DT) layered inertial confinement fusion (ICF) targets] using foam shells filled with liquid DT; to the best of knowledge, these designs offer the only target solutions where the cost is consistent with the IFE mass production requirements.

There has been major progress made over the last several years in understanding ICF implosions based on extensive research done in the field of high-energy-density plasmas (HEDP) and ICF using well-diagnosed integrated and physics focused experiments at the major laser facilities, including the National Ignition Facility (NIF) [1], Omega [2], and NIKE [3] at the U.S. Naval Research Laboratory (NRL). Most importantly, ignition demonstration on the NIF in August 2021 put to rest physics uncertainty in ability to ignite a capsule that couples only a few kJ of energy into the hot spot using a MJ-class laser facility. The recent progress was supported by the advances in multi-dimensional code development and theoretical understanding of 3-D hydrodynamic flow, various LPI processes, and fundamental properties of matter at extreme conditions. This success makes a strong case for developing the next-generation drivers that are capable of overcoming the major roadblocks in achieving high gains in the laboratory using the ICF approach.

For many years, progress in ICF was accomplished mainly by building bigger and more powerful (hence, more expensive) laser systems. Our proposed approach is different: we consider achieving the IFE target performance objectives by using the innovative broadband technologies that will couple significantly more energy to the fuel using less laser energy than currently available on the NIF. This will drastically change the landscape of fusion energy research, making the new laser technologies a compelling tool in achieving the challenging goals of energy production using ICF implosions.

Target gain requirement – The target gain G requirement follows from the following simple argument [4]: if $\eta_D P_{in}$ is the total laser energy incident on target, then, the target fusion output is $G\ \eta_D P_{in}$, where P_{in} is the electrical power required to run the laser, η_{D} is the driver "wall-plug" efficiency. Next, assuming a commonly used 40% conversion of the fusion power to electric power, the total electric power produced by a power plant is $P_{out} \approx\ 0.4\ G\ \eta_D P_{in}$. Some fraction of this output power (studies have estimated this to be ~ 0.25) needs to be circled back to run the laser and the other plant components, giving $P_{in} = 0.25\ P_{out} = 0.1\ G\eta_D P_{in}$ or $\boldsymbol{G\eta_D \approx 10.}$ The expected "wall-plug" efficiency for the laser driver systems can be as high as 10% or more. This leads to a requirement of $G > 100$ to be necessary for IFE applications.

ICF fundamentals – To achieve ignition in a conventional ICF implosion, a spherical shell filled with a frozen DT layer is driven inward either by x rays emitted inside a hohlraum by illuminating its high-Z walls with laser irradiation (laser indirect drive, LID) or by laser irradiation directly impinging on the target (direct drive, LDD) [5]. The shell is accelerated by the drive or ablation pressure p_{a} resulting from these radiation sources, converting driver energy to the shell kinetic energy E_{k}. As shell converges the pressure in the central void region builds up until it starts to exceed the ablation pressure. At this point, an outgoing shock wave is launched into the shell, decelerating it and converting its kinetic energy into internal energy of the central region (hot spot). If the hot-spot temperature and mass density are high enough, the production rate of alpha particles (fusion product of D+T nuclear reactions) is sufficient to self-heat the hot spot and trigger a burn wave into the main fuel which contains the majority of the fuel mass.

Challenges in achieving high gains in ICF – To clarify the main objectives of the proposed work and highlight the path forward for achieving high gains required for IFE designs, we briefly review the main physics of the high-gain designs. Achieving high gains in ICF implosions requires maximizing DT fuel burnup fraction f_{burn}, which depends on fuel areal density (ρR) at peak fuel compression, $f_{\text{burn}} \approx \rho R/(\rho R+7\ \text{g/cm}^2)$ [5]. Therefore, achieving a burnup fraction of more than 1/4 will require $\rho R > 2.4\ \text{g/cm}^2$. The target gain (defined for energy production application as ratio of energy in neutron yield to the laser energy) is $G = M_{\text{burn}}\epsilon_{DT}/E_L$, where $\epsilon_{DT} = 2.75 \times 10^{11}\text{J/g}$ is the neutron energy per gram produced by DT fusion, $M_{\text{burn}} = f_{\text{burn}}M_{\text{DT}}$, and M_{DT} is fuel mass at peak compression. The fuel mass in an ICF implosion can be simply estimated by assuming that the drive pressure p_{a} accelerates the shell to reach implosion velocity v_{imp} over pulse duration Δt_{acc}. These are related through Newton's law as $M_{\text{DT}}v_{\text{imp}}/\Delta t_{\text{acc}} \sim 4\pi R_{\text{shell}}^2 p_a$, where R_{shell} is the initial shell radius. Writing laser energy as $E_L \simeq P_L \Delta t_{acc}$, where P_{L} is the peak laser power, Eq. (1) leads to (including the numerical coefficient)

$$M_{DT} \simeq 0.2\ p_a E_{\text{L}}/(V_{\text{imp}}I), \quad (1)$$

where $I \simeq P_L/4\pi R_{shell}^2$ is the peak laser drive intensity. Then, target gain becomes

$$G \simeq 180\frac{f_{\text{burn}}}{I_{15}}\left(\frac{p_a}{100\ \text{Mbar}}\right)\left(\frac{v_{\text{imp}}}{3 \times 10^7\text{cm/s}}\right)^{-1}, \quad (2)$$

where I_{15} is peak laser intensity in units of 10^{15} W/cm^2. This estimate shows that in addition to maximizing the burnup fraction (and, therefore, areal density), higher drive pressures and lower implosion velocities are favorable to achieving higher gains because they enable larger fuel mass to be used in the target design. The drive pressure p_a in an LDD ICF implosion depends on laser intensity and is limited by various laser-plasma interaction processes (such as SBS, SRS, and two plasmon decay instability). Calculations show [6] that ablation pressure for laser illumination with wavelength of $\lambda_L = 351$ nm scales with laser intensity as

$$p_a(Mbar) = 210\, I_{15}^{0.69}, \qquad p_{a,\text{CBET}}(Mbar) = 82\, I_{15}^{0.57}, \quad (3)$$

where $p_{a,CBET}$ is calculated including coupling losses caused by cross-beam energy transfer (CBET) [7]. Substituting such scaling into Eq. (3) and using $f_{\text{burn}} = 1/4$ gives

$$G \simeq 95\, I_{15}^{-0.31} \left(\frac{v_{imp}}{3 \times 10^7}\right)^{-1}, \qquad G_{CBET} \simeq 37\, I_{15}^{-0.43} \left(\frac{v_{imp}}{3 \times 10^7}\right)^{-1}. \quad (4)$$

This shows that to get gain of 100, the drive intensity without LPI losses needs to be $I_{15} < 1$ with $p_a < 210$ Mbar, while with CBET losses, this scaling gives a misleading conclusion that the intensity should drop to $I_{15} < 0.1$ with $p_a < 22$ Mbar. Using designs with low drive pressure is not practical since they require very large laser energies to ignite. This can be shown by using the ignition criterion. Hot-spot initiates a burn wave into the main fuel when self-heating is achieved and power of alpha particles deposited inside the hot spot exceeds the loss power (due mainly to thermal conduction, radiation, and PdV work if the shell starts to expand). This condition, known as Lawson's criterion [8], can be written for ICF implosions as [9]

$$p_{\text{hs}} R_{\text{hs}} > 1 \text{ Gbar} \times \text{cm}, \quad T_i > 4 \text{ keV}, \quad (5)$$

where p_{hs}, E_{hs}, and T_{i} are the hot-spot pressure, internal energy, and ion temperature, respectively. Substituting scaling relations for the hot-spot pressure and radius with implosion parameters [6] gives

$$p_{hs} R_{hs}(\text{Gbar} \times \text{cm}) < 0.6 \left(\frac{E_k}{10 \text{ kJ}}\right)^{\frac{1}{3}} \left(\frac{v_{imp}}{3 \times 10^7}\right)^{\frac{8}{3}} \alpha^{\frac{4}{5}}, \quad (6)$$

Where $E_k$is shell kinetic energy and $\alpha = P/P_F$ is fuel adiabat defined as ratio of fuel pressure to Fermi-degenerate pressure at shell density. The target performance is maximized when the outgoing shock wave, launched into the shell at the onset of deceleration, has not broken out of the main shell prior to the hot spot reaching peak compression. Otherwise, the main shell prematurely decompresses, starting from the outer surface, limiting shell convergence ratio, hot-spot pressure, and peak areal density. The fraction of the shell overtaken by the shock at peak hot-spot convergence is given by [9] $\frac{M_s}{M_{DT}} \simeq 1.2 \left(\frac{v_{imp}}{3 \times 10^7 \text{cm/s}}\right)^{\frac{4}{3}} \alpha^{-\frac{2}{5}} \left(\frac{p_a}{100 \text{ Mbar}}\right)^{-\frac{13}{15}}$. Requiring that the shock is inside the shell at peak compression, $M_s < M_{DT}$ (the product $p_{hs} R_{hs}$ as defined by Eq. (6) is maximized in this case), defines the limit on the implosion velocity for the optimal design, $v_{imp} < 2.6 \times 10^7 \text{cm/s}\ \alpha^{0.3} \left(\frac{p_a}{100 \text{ Mbar}}\right)^{0.65}$. Using this condition in Eq. (6) gives the upper limit on the ignition parameter, $p_{hs} R_{hs} < 0.4 \left(\frac{E_k}{10 \text{ kJ}}\right)^{\frac{1}{3}} \left(\frac{p_a}{100 \text{ Mbar}}\right)^{\frac{5}{3}}$. Then, the ignition criterion shown in Eq. (5) leads to the requirement on shell kinetic energy,

$$E_k(\text{kJ}) > 156 \left(\frac{p_a}{100 \text{ Mbar}}\right)^{-5}. \quad (7)$$

Such a strong dependence of shell kinetic energy required for ignition on ablation pressure emphasizes the necessity of reducing coupling losses and maximizing ablation pressure in an ICF implosion. This relation sets the requirement for ablation pressure: accelerating the fuel mass M_{DT}, sufficient to achieve $G = 100$ on a MJ-class laser facility, to implosion velocity $v_{imp} \simeq 3 \times 10^7$cm/s results in $E_k \sim 70$ kJ. Then, to achieve ignition, according to Eq. (7), ablation pressures must exceed $p_a > 120$ Mbar. According to Eqs. (4) and (5), it is not possible to satisfy $p_a > 120$ Mbar with $G > 100$ when CBET losses are included. Thus, the only **path for IFE target design using a conventional hot-spot approach is mitigating coupling losses due to LPI and maximizing ablation pressure**. Even with CBET losses fully mitigated, reaching drive conditions consistent with a $G > 100$ design could be challenging because of the hydrodynamic instabilities. In the examples shown above, we have assumed the fuel burnup fraction of 1/4, which requires $\rho R > 2.4$ g/cm^2. For $E_L \sim 1$ MJ this implies keeping the fuel at Fermi degeneracy, $\alpha \simeq 1$, and shell inflight aspect ratio of IFAR > 24, well above the stability threshold limit observed in current LDD experiments on OMEGA [9]. Addressing the stability issues will require further increase in the ablation pressure [above scaling law shown in Eq. (5)] and increasing fuel areal density (to enhance the burnup fraction).

Modeling – LLE has developed state-of-the-art computational tools to simulate integrated LDD experiments as well as study fundamental physics of ICF implosions. LDD implosions on OMEGA and NIF are simulated using **radiation-hydrodynamics codes** (1-D *LILAC* [10], 2-D *DRACO* [11], and 3-D *ASTER* [12] as well as 3-D *HYDRA* [13] developed at LLNL and enhanced by LLE) which include a 3-D laser ray tracing with CBET, non-local heat conduction [14], first-principles EOS (FPEOS) and opacity tables [15], and hot-electrons and charged particle transport. The **modeling of laser–plasma interactions** is performed with the laser–plasma simulation environment (*LPSE*) [16]. *LPSE* was designed from first principles to capture the unique combination of physical processes required to study LPI. *LPSE* includes the following features: non-paraxial wave propagation, injection of arbitrary and realistic laser pulses from OMEGA or NIF beam geometries, a reduced kinetic model for hot-electron generation, and multi-level parallelism for shared and distributed memory systems. *LPSE* can simulate individual or concurrent laser–plasma interactions, including CBET, SRS, SBS, two-plasmon decay, resonance absorption, and filamentation, each of which has been verified with analytical models for the growth rates and thresholds. In addition, to assess the accuracy of **fundamental material properties** and to provide input to hydrodynamic code simulation, systematic first-principles calculations of **equation-of-state, opacity, thermal conductivity, and stopping power** have been carried out for a wide range of densities and temperatures by using state-of-the-art quantum many-body methods such as density functional theory (DFT), path integral Monte Carlo (PIMC), and time-dependent DFT [17].

Advanced laser technology – Based on more than 15 years of experience of layered cryogenic implosions on OMEGA and LDD experiments on the NIF, the major shortcomings of the current drivers and target designs have been identified and as a result, new laser technologies are under development. Existing simulations [18, 19] show that these technologies address most of the problems that prevent ICF implosions from reaching the performance consistent with the IFE requirements. The proposed work will pursue designs with the following main elements in addressing the current ICF challenges:

1. **Use of broadband laser technologies** to mitigate deleterious effects of LPI, including reduction in laser coupling and ablation pressure, generating hot electrons, and reducing laser imprint. Several options are currently being considered for new broadband laser drivers. These include (a) **Optical parametric amplifiers (OPAs)** followed by frequency conversion deliver broadband spectrally incoherent pulses at 351 nm and high efficiency of ~ 10%. It is also predicted to produce very large bandwidth of 12 THz ($\Delta\omega/\omega$ ~ 1.5%) when frequency-tripled to λ_L =351 nm. Current simulations using the LPI code LPSE predicts that such

bandwidth is sufficient to mitigate coupling losses caused by CBET, increasing laser coupling to above 90% [18]; and (b) The **StarDriver® concept** [20] that allows designs to use many beams with different wavelengths to effectively create broadband illumination and minimize the impact of LPI as well as beam overlap nonuniformity.

2. **Use of multi-color drivers**. Using lasers with a longer-wavelength at the beginning of the drive creates a larger conduction zone (the distance between the laser-deposition region and the ablation front) and more efficient thermal conduction smoothing for nonuniformities seeded by laser imprint and target defects. At the same time, shorter wavelengths used in the main, higher-intensity pulse lead to higher drive efficiency (the laser is absorbed at higher densities for shorter laser wavelengths) and lower LPI gains.

Targets – target production cost is one of the key elements to consider to be cost-competitive in the energy production field. Nominal ICF designs have multiple-layer ablators and a cryogenic DT ice layer that must satisfy very rigorous uniformity requirements. Right now, these targets are very costly, time consuming to produce, and, therefore, not appropriate for IFE. Resent design effort has resulted in very promising path of using wetted foam targets filled with liquid DT. Olson *et al.*,[21] have suggested a foam shell wetted with liquid DT, while Goncharov *et al*., [22] have proposed a new design concept – dynamic shell formation design where the target consists of a foam shell filled with liquid DT, forming a nearly homogeneous-density ball. The shell in this design is formed dynamically by appropriately shaping the laser pulse.

To summarize, the target design path for laser drive IFE applications must include:

1) **Mitigation of coupling losses** caused by LPI. This will require advanced laser technologies, including broadband laser illumination. Laser coupling must not only be high to maximize hydrodynamic efficiency (ratio of shell kinetic energy to laser energy) but also efficient to produce ablation pressures in excess of 200 Mbar at laser intensities $I < 10^{15}$W/cm^2.
2) **Improved target robustness** which requires an additional ablation pressure increase to 200 to 300 Mbar range using, for example, beam zooming (reduction in the beam focal spot to match shrinking inflight target size). For example, increasing ablation pressure by 25% will allow reduction in the fuel burn up fraction and peak areal density by $\sim\sqrt{2}$ which is equivalent to an increase in fuel adiabat from $\alpha = 1$ to $\alpha = 2$. Both an increase in ablation pressure and fuel adiabat leads to lower IFAR and more stable implosions. In addition, broadband lasers are predicted to smooth single-beam, short-scale **laser imprint** at dramatically faster rates (over a few picoseconds), eliminating the necessity to introduce additional speckle-smoothing techniques (SSD [23] and polarization smoothing [24]), simplifying laser systems and reducing their cost.
3) **An increase in areal density** (required to enhance burn up fraction) can be accomplished not only by a reduction in adiabat, but also by increasing shell convergence with lowering density in the central region of the shell. The new target design concept, dynamic shell formation, allows the central region density to be significantly reduced by extending the density relaxation phase of the dynamic shell design.
4) **Simplified targets** which for the high-gain designs will include foams filled with liquid DT. Proposed wetted foam designs [21] and dynamic shell concept [22] do not required DT ice layers. These designs offer the only target solutions where the cost is consistent with the IFE mass production requirements.

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