Inertial Confinement Fusion—Experimental Physics: Laser Drive

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Glossary

Areal density The product of the plasma density and thickness.
Ignition Ignition occurs when the yield amplification from the alpha heating exceeds twenty.
Plasma A plasma is a quasineutral gas of charged and neutral particles which exhibits collective behavior due to the long-range electromagnetic forces.

Introduction

In the last seven decades research and development of controlled thermonuclear fusion has been pursued in the laboratory as an alternative energy resource to fossil fuels using magnetically-confined plasmas (Meade, 2009), such as the tokamak (Rutherford, 1980). Since the advent of the laser in the 1960s, inertial confinement fusion schemes using lasers have been investigated (Nuckolls et al., 1972; Kidder, 1974, 1976; Lindl et al., 1992). In the last few decades, inertial confinement fusion using pulsed power has been pursued (Slutz et al., 2010; Gomez et al., 2021). Thermonuclear fusion of the hydrogen isotopes deuterium (D) and tritium (T) involves nuclear fusion of the ions in a high-temperature plasma, where the thermal energy of the ions in the plasma overcomes their long-range Coulomb repulsion and the short-range nuclear force fuses the ions. The high fusion reaction rate of deuterium and tritium (i.e., $D + T \rightarrow {}^4He + n$) relative to other fusion reactants makes it a practical fuel choice for laboratory fusion plasmas and the majority of fusion research has used this fuel. Nuclear energy is released in the reaction, since the DT fusion converts almost 0.4% of the mass of the hydrogen isotopes into energy through Einstein's mass-energy relationship, $\Delta E = \Delta mc^2$, where ΔE is the energy liberated in the nuclear fusion reaction, Δm is the difference in the mass of the reactants and the fusion products, and c is the speed of light. The alpha particle (${}^4He$) and the neutron fusion products have birth energies of 3.5 and 14.1 MeV, respectively. Thermonuclear fusion plasmas are designed to absorb the energy of the alpha particle to further increase the plasma temperature leading to more fusion reactions (i.e., alpha heating). The viability of energy production in a fusion plasma is quantified by the Lawson criterion, which compares the rate of energy generation from nuclear fusion to the rate of energy loss in the plasma (Lawson, 1957). For ICF, these loss mechanisms include radiation, thermal conduction, and hydrodynamic expansion. Future inertial fusion power plants would use the energetic neutrons to bombard a blanket containing lithium surrounding the fusion plasma to breed tritium fuel using the following nuclear reaction: $n + {}^6Li \rightarrow {}^4He + T$ (Atzeni, 2021). The energy that the neutrons deposit in the blanket can be extracted with a heat exchanger and used boil water for a steam turbine to generate electricity. The three main approaches of inertial confinement fusion are laser direct drive (Goncharov et al., 2014, 2017; Craxton et al., 2015; Regan et al., 2016, 2019; Bose et al., 2016; Campbell et al., 2017, 2021; Gopalaswamy et al., 2019; Campbell, 2021), laser indirect drive (Moses et al., 2009; Glenzer et al., 2010; Meezan et al., 2010; Michel et al., 2010; Haan et al., 2011; Edwards et al., 2011; Landen et al., 2011; Edwards et al., 2013; Hurricane et al., 2014, 2019a,b, 2021; Meezan et al, 2015; Le Pape et al., 2018; Landen et al., 2020; Patel et al., 2020; Town, 2020; Zylstra et al., 2021; Landen et al., 2021), and magnetic direct drive (Slutz et al., 2010, 2018; Sinars et al., 2020; Gomez et al., 2021). This chapter concentrates on the current status of the experimental physics in inertial confinement fusion involving lasers, while magnetic direct drive is covered elsewhere (Gomez et al., 2021).

Laser-driven inertial confinement fusion creates thermonuclear conditions in the laboratory by irradiating a spherical target containing a layer of thermonuclear fuel (Gibson et al., 2009; Johal et al., 2009; Harding et al., 2005, 2018) as shown in Fig. 1 with high-intensity lasers or X-rays (Atzeni, 2021; Tikhonchuk, 2021). The physical dimensions and composition of the ablator depends on the energy incident on the target and the photon wavelength of the driver. Inertial confinement fusion implosions are analogous to a spherical rocket, where the rocket fuel (the ablator) is energized by the incident driver energy and the DT fuel is the payload. The initial pursuit of laser fusion involved laser direct drive, where the outer surface of the target is uniformly irradiated with multiple, temporally-shaped laser beams having a peak, overlapped intensity of $< 10^{15}$ watts/cm^2 on the nanosecond time scale. As mentioned above, the resulting laser-ablation process causes the target to accelerate and implode via the rocket effect, reaching

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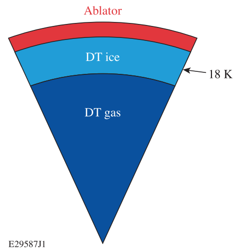

Fig. 1 Schematic of a laser-driven inertial confinement fusion target for central hot-spot ignition, consisting of an ablator surrounding a cryogenic layer of deuterium (D) and tritium (T). The central void contains DT gas.

a peak implosion velocity in the 300 to 500 km/s range depending on the implosion design (Tikhonchuk, 2021). In the early days of inertial confinement fusion research, challenges with nonuniformities in the laser drive incident on the target surface motivated the development of laser indirect drive, whereby the laser energy is converted to X-rays in a high-atomic number radiation case, called a hohlraum, with a near-Planckian spectrum having a temperature of about 300 eV to drive the ablation process (Lindl et al., 1992, 2004; Lindl, 1995, 1998). The two laser-driven, inertial confinement fusion techniques are highlighted schematically in Fig. 2. The spherical concentric layers of a laser-direct-drive inertial confinement fusion target typically consist of a central region of a near equimolar DT vapor surrounded by a cryogenic DT-fuel layer and a thin, nominally plastic (CH) layer, called the ablator (see Fig. 1). The laser-indirect-drive target is similar except the ablator is thicker, due to the efficient x-ray driven ablation, and has multiple concentric layers designed to optimize the implosion (Lindl, 1998; Town, 2020; Tikhonchuk, 2021). In both cases, as the DT-fuel layer decelerates, the initial DT vapor and the fuel mass thermally ablated from the inner surface of the ice layer are compressed and form a central hot-spot plasma, in which fusion reactions occur for a few tenths of a nanosecond around stagnation. The energy coupling from the laser to the hot-spot plasma can be adversely affected by laser plasma instabilities (Kruer, 2003; Tikhonchuk, 2021), hydrodynamic instabilities (Tikhonchuk, 2021), and low- and high-mode drive asymmetries (Town, 2020; Campbell, 2021; Tikhonchuk, 2021). Inertial confinement fusion relies on the 3.5 MeV DT-fusion alpha particles depositing their energy in the hot-spot plasma, causing the hot-spot temperature to rise sharply and a thermonuclear burn wave to propagate out through the surrounding nearly-degenerate, cold dense DT fuel as highlighted in Fig. 3, producing significantly more energy than was used to heat and compress the fuel. The inertia of the compressed DT shell confines the hot-spot plasma for a timescale that is long enough for alpha heating to trigger the ignition instability and achieve energy gain (Town, 2020; Campbell, 2021; Tikhonchuk, 2021; Atzeni, 2021). A burning plasma has a yield amplification due to alpha heating greater than 3.5 (Betti et al., 2015; Hurricane et al., 2019b). Alpha amplification is a metric to describe the increase in overall fusion beyond that due to the hydrodynamic work done during the implosion. An ignited plasma has a yield amplification due to alpha heating in the range of 15 to 25 depending on the implosion design (Christopherson et al., 2019). The total fusion yield depends on the burn up fraction of the DT fuel, which is

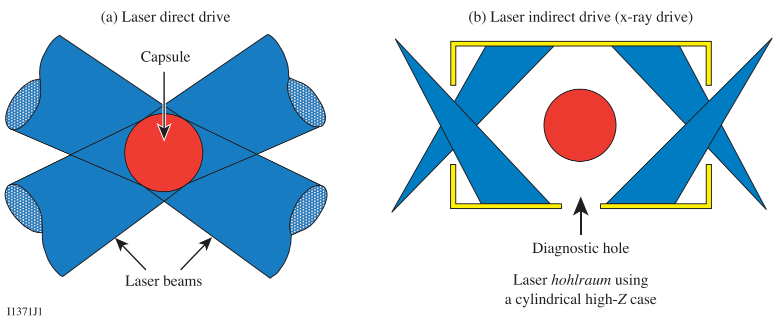

Fig. 2 Schematics highlighting the two laser-driven, inertial confinement fusion techniques: laser direct drive (left panel) and laser indirect drive (right panel).

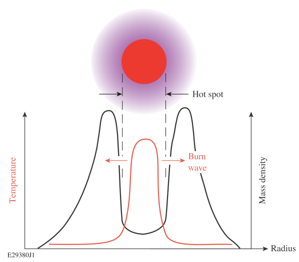

Fig. 3 Inertial confinement fusion relies on the 3.5 MeV DT-fusion alpha particles depositing their energy in the hot-spot plasma, causing the hot-spot temperature to rise sharply and a thermonuclear burn wave to propagate out through the surrounding nearly-degenerate, cold dense DT fuel as highlighted with the spatial profiles of the temperature and density.

a function of the total areal density of the compressed DT fuel (Lindl, 1998). The onset of central-hot-spot ignition is predicted to occur when the product of the temperature and areal density of the hot-spot plasma reach a minimum of 5 keV × 0.3 g/cm^2 (Betti et al., 2002; Lindl et al., 2004; Atzeni and Meyer-ter-Vehn, 2004). A generalized Lawson ignition parameter (hot-spot pressure x hot-spot confinement time) is used to quantify the proximity to ignition, where a value of unity corresponds to ignition (Betti et al., 2015). Here the pressure and confinement time are estimated without accounting for alpha heating to assess the pure hydrodynamic performance of the implosion. The ignition threshold factor (Spears et al., 2012; Lindl et al., 2014, 2018) used for laser indirect drive implosions is related to the generalized Lawson ignition parameter (Patel et al., 2020).

Central-hot-spot ignition is presently the main line research of laser-driven inertial confinement fusion. Other laser driven inertial confinement fusion techniques under investigation include shock ignition (Betti et al., 2007; Atzeni et al., 2014), fast ignition (Tabak et al., 1994; Kodama et al., 2002; Theobald et al., 2011, 2014), and volumetric ignition with multiple-shell targets (Varnum et al., 2000; Amendt et al., 2002; Molvig et al., 2016; Montgomery et al., 2018; Hu et al., 2019).

This chapter concentrates on the laser-driven central-hot-spot ignition experiments involving implosions of layered DT cryogenic targets (Gibson et al., 2009; Johal et al., 2009; Harding et al., 2005, 2018) conducted at the 192-beam, 2.1-MJ, 500-TW, 351-nm National Ignition Facility (Campbell and Hogan, 1999; Spaeth et al., 2016) and the 60-beam, 30-kJ, 30-TW, 351-nm OMEGA Laser System (Boehly et al., 1997). These lasers are shown in Fig. 4 and described elsewhere (Finnegan, 2021). A primary goal of the National Ignition Facility is to achieve ignition and modest gain using the laser-indirect-drive ignition approach first and then laser direct drive.

Laser-indirect-drive ignition-scale implosions have been performed on the National Ignition Facility since 2009 (Moses et al., 2009; Glenzer et al., 2010; Meezan et al., 2010; Michel et al., 2010; Haan et al., 2011; Edwards et al., 2011, 2013; Landen et al., 2011, 2020, 2021; Hurricane et al., 2014, 2019a, b, 2021; Meezan et al., 2015; Le Pape et al., 2018; Patel et al., 2020; Town, 2020; Zylstra et al., 2021). The laser-indirect-drive implosions on the National Ignition Facility are designed to investigate alpha heating, burning plasma, and ignition target designs (Hurricane et al., 2014, 2019a, b, 2021; Patel et al., 2020; Town, 2020; Zylstra et al., 2021). These experiments have demonstrated alpha heating and are accessing the burning plasma regime, which is an encouraging development in the pursuit of the grand research challenge of ignition.

Several facility enhancements are required on the National Ignition Facility to conduct laser-direct-drive ignition-scale implosions. Progress made with laser direct drive over the last decade motivates laser direct drive implosions on the National Ignition Facility (Goncharov et al., 2014, 2017; Craxton et al., 2015; Regan et al., 2016, 2019; Bose et al., 2016; Campbell et al., 2017; Gopalaswamy et al., 2019; Campbell, 2021; Campbell et al., 2021), since laser direct drive increases the amount of energy coupled to the hot spot by a factor of several over the laser indirect drive, which enables increased mass in the hot spot, leading to a potential increase in the margin for ignition. Energy coupling from the laser to the implosion capsule is an important consideration in inertial confinement fusion. The larger imploded mass and increased coupled energy results in lower required convergence and hot-spot pressure and the possibility of achieving MJ yields at implosion adiabats greater than three (Goncharov et al., 2014, 2016, 2017). The adaibat is the ratio of the pressure in the cold DT fuel to the Fermi-degenerate pressure, which is the minimum energy density due to the degeneracy of the electrons that can be achieved (Tikhonchuk, 2021). Understanding the laser and target physics requirements for ignition is important for the inertial confinement fusion research program on the National Ignition Facility and for the research and development of a next-generation laser facility designed to achieve a robust burning-plasma platform and high yield (i.e., >200 MJ).

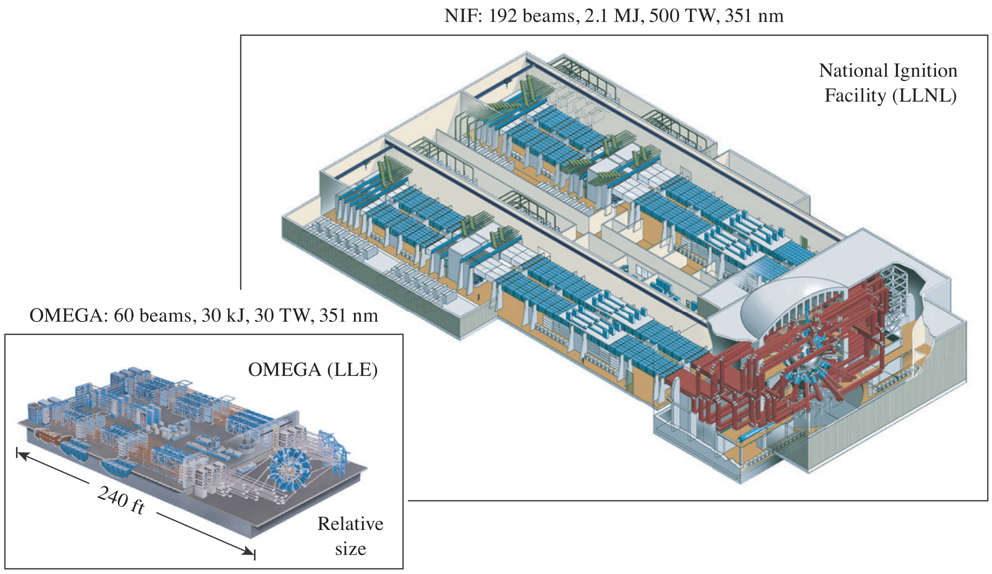

Fig. 4 Schematics of the 60-beam, 30-kJ, 30-TW, 351-nm OMEGA Laser System at the University of Rochester's Laboratory for Laser Energetics (LLE) and the 192-beam, 2.1-MJ, 500-TW, 351-nm National Ignition Facility at the Lawrence Livermore National Laboratory (LLNL).

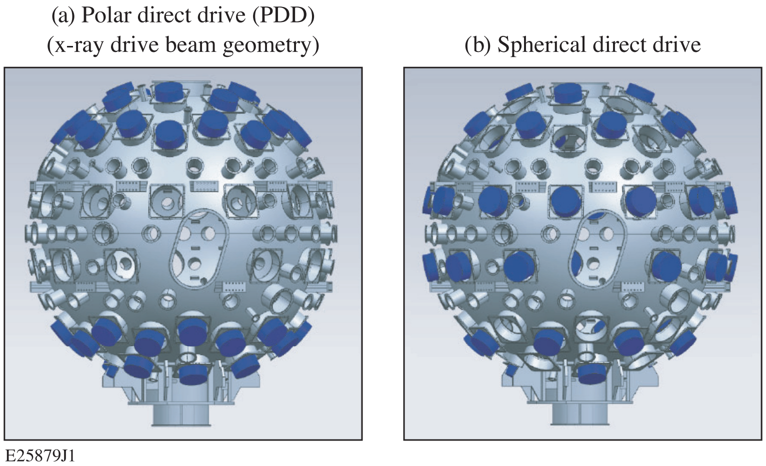

Fig. 5 Schematics of the NIF target chamber with the blue circles highlighting the beam configuration for laser indirect drive (X-ray drive) and Polar Direct Drive (left panel) and the spherically-symmetric beam configuration for laser direct drive, called spherical direct drive (right panel) on the National Ignition Facility. The current beam configuration on the National Ignition Facility is optimized for laser indirect drive (left panel).

Although the beam configuration on the National Ignition Facility is optimized for laser indirect drive with a right circular cylindrical hohlraum by arranging the beams around the poles of the target chamber as illustrated with the blue circles in the left panel of Fig. 5, it can also be used for a variant of laser direct drive called Polar Direct Drive (Skupsky et al., 2004; Craxton et al., 2005; Craxton and Jacobs-Perkins, 2005; Cobble et al., 2012; Radha et al., 2012, 2013, 2016; Krasheninnikova et al., 2014; Hohenberger et al., 2015; Rosenberg et al., 2018; Marozas et al., 2018a, b). The optimal arrangement for laser direct drive with the beams uniformly distributed around the target chamber is highlighted with the blue circles in the right panel of Fig. 5, called spherical direct drive. Although the NIF target chamber has ports for spherical illumination, switching between these two beam geometries requires a major, resource-intensive engineering effort. The laser direct drive ignition approach on the National Ignition Facility is Polar Direct Drive for the next five to ten years. In the Polar Direct Drive configuration, which is also studied in experiments on OMEGA using only 40 beams (Marshall et al., 2006, 2016; Radha et al., 2012), a subset of the beams is repointed toward the equator of the target to recover the spatial uniformity of the on-target, overlapped laser-drive intensity. Several of the key physics aspects of laser direct drive, including energy coupling, laser plasma instabilities, and hydrodynamic instabilities, at ignition-relevant scale lengths are studied on the National Ignition Facility using a polar-direct-drive configuration (Radha et al., 2013, 2016; Krasheninnikova et al., 2014; Hohenberger et al., 2015; Rosenberg et al., 2018, Marozas et al., 2018a, 2018b; Campbell, 2021).

Significant laser and cryogenic target upgrades are required to perform high-convergence (i.e., convergence ratio > 15), laser-direct-drive implosions using the polar-direct-drive configuration for burning plasma and ignition on the National Ignition Facility (Campbell, 2021). Planning is underway to implement these polar direct drive facility enhancements to the National Ignition Facility over the next 10 years (Campbell, 2021). Hot-spot formation for spherically symmetric, laser-direct-drive, DT-layered implosions is studied on the OMEGA laser system using hydrodynamically-scaled ignition targets (Nora et al., 2014; Goncharov et al., 2014; Regan et al., 2016; Bose et al., 2016; Gopalaswamy et al., 2019), since OMEGA does not have enough laser energy to assemble an ignition-scale hot-spot plasma. A primary goal of OMEGA is to investigate subscale laser-direct-drive implosions and the underpinning fundamental physics of implosion designs that are hydrodynamically equivalent (i.e., maintaining the same shell convergence, hot-spot pressure, shell adiabat, and implosion velocity) to burning plasma and ignition designs on MJ-scale lasers in both polar and spherical illumination geometries (Campbell, 2021).

This chapter presents a concise overview of the current status of the experimental physics research for central-hot-spot ignition using laser-driven inertial confinement fusion. More detailed descriptions can be found in recent review reports for laser direct drive (Campbell, 2021) and laser indirect drive (Town, 2020). The energy coupling from the laser to the hot-spot plasma and the degradation mechanisms to implosion performance from laser plasma instabilities, hydrodynamic instabilities, and low-mode drive and target asymmetries (Tikhonchuk, 2021) are discussed for the two laser-driven inertial confinement fusion approaches using central hot-spot ignition. Section "Laser-Direct-Drive Research" presents the performance of laser-direct-drive implosions on OMEGA that are hydrodynamically-scaled to the 2.0 MJ of laser energy on the National Ignition Facility (Goncharov et al., 2014; Igumenshchev et al., 2016; Regan et al., 2016; Bose et al., 2016; Gopalaswamy et al., 2019; Campbell, 2021; Campbell et al., 2021). These hydrodynamically-scaled, spherical direct drive implosions are predicted to achieve a threefold amplification in fusion yield due to alpha heating, corresponding to a total fusion yield of about 0.6 MJ (Gopalaswamy et al., 2019; Campbell, 2021). The energy-scaled, generalized Lawson ignition parameter (Betti et al., 2015; Bose et al., 2016) for laser direct drive implosions on OMEGA is approximately 0.75 (Campbell, 2021). The research and development of high-energy, solid-state laser drivers that mitigate laser–plasma instabilities and laser-beam imprint via enhanced spectral bandwidth to increase the implosion performance are also discussed in this chapter (Follett et al., 2018, 2019; Bates et al., 2018; Dorrer et al., 2020). Section "Laser Indirect Drive Research" summarizes the progress of the laser-indirect-drive approach on the National Ignition Facility demonstrating alpha heating and accessing the burning plasma regime with ~2 MJ of laser energy, corresponding to ~ 0.06 MJ of total fusion yield, and the quest for the ignition challenge (Moses et al., 2009; Glenzer et al., 2010; Meezan et al., 2010, 2015; Michel et al., 2010; Haan et al., 2011; Edwards et al., 2011, 2013; Landen et al., 2011; Hurricane et al., 2014; Le Pape et al., 2018; Hurricane et al., 2019a, b; Landen et al., 2020, 2021; Patel et al., 2020; Town, 2020; Zylstra et al., 2021; Hurricane et al., 2021). The generalized Lawson ignition parameter for laser-indirect-drive implosions on the National Ignition Facility is 0.75 (Patel et al., 2020). The path forward for ignition on the National Ignition Facility with laser indirect drive is also discussed.

Laser-Direct-Drive Research

As mentioned in the introduction, the high-intensity lasers are incident directly on the target for the laser-direct-drive approach. There are four stages to the resulting implosion: initial plasma formation, acceleration, deceleration, and stagnation, which are highlighted in Fig. 6 (Campbell, 2021; Tikhonchuk, 2021). Depending on the implosion design, the peak shell velocity at the end of the acceleration phase is in the 300-500 km/s range. After the laser ionizes the target surface and the coronal plasma is formed, the laser light is absorbed in the under-dense plasma via inverse Bremsstrahlung and a fraction of the absorbed energy flows to the ablation surface via electron thermal conduction. The coronal plasma typically absorbs 60–70% of the laser energy and hydrodynamic efficiency of converting that absorbed laser energy to inward kinetic energy of the shell via the rocket effect is about 9%. This gives a conversion efficiency of incident laser energy to shell kinetic energy of about 6% for laser direct drive. The laser ablation launches a shock wave into the target. As the coronal plasma forms, spatial nonuniformities in the laser irradiation can imprint on the ablation surface (i.e., laser imprint) and mass perturbations on the target from microscopic debris, the support stalk, and the fill tube seed the Richtmyer-Meshkov hydrodynamic instability (Richtmyer, 1960; Meshkov, 1969; Goncharov, 1999). The key target physics during the initial plasma formation are laser uniformity, laser absorption, energy coupling, ablation, shock propagation, laser imprint, and the Richtmyer-Meshkov hydrodynamic instability. The time history of the laser intensity on target, shown in the right panel of Fig. 6, is designed to minimize the rise in the entropy of the compressed shell, quantified by the shell adiabat, in order to minimize the amount of laser energy needed for ignition (Tikhonchuk, 2021). Although lower-adiabat ignition target designs require less laser energy to achieve ignition (Herrmann et al., 2001, Betti et al., 2002), they are more susceptible to hydrodynamic instabilities (Betti et al., 1998).

After the shock wave reaches the inside layer of the DT shell and the rarefaction wave returns to the ablation surface, the DT shell begins to accelerate (see Fig. 6). Mass perturbations at the ablation surface due to target defects and laser nonuniformities can seed the Rayleigh Taylor hydrodynamic instability (Rayleigh, 1945; Taylor, 1950; Cole et al., 1982). During the acceleration phase, as mentioned above, the intensity of the laser irradiation may exceed the thresholds to excite electron waves in the plasma via the Stimulated Raman Scattering or the Two Plasmon Decay instability and ion waves in the plasma via the Stimulated Brillouin Scattering (Kruer, 2003). Excitation of ion waves in the plasma can divert energy flow from the laser to the ablation front. In the cross-beam energy transfer process (Igumenshchev et al., 2010, 2012; Froula et al., 2012), nonabsorbed light that is reflected or scattered from its critical surface or refracted from the under-dense plasma acts as an electromagnetic seed for the stimulated Brillouin scatter of incoming (incident) light (Randall and Albritton, 1981). Cross beam energy transfer has been shown to reduce the target absorption and resulting ablation pressure of laser direct drive targets by as much as 40% on OMEGA (Igumenshchev et al., 2010, 2012, Froula et al., 2012) and 60% on polar direct drive targets for the National Ignition Facility (Radha et al., 2016). Excitation of electron waves

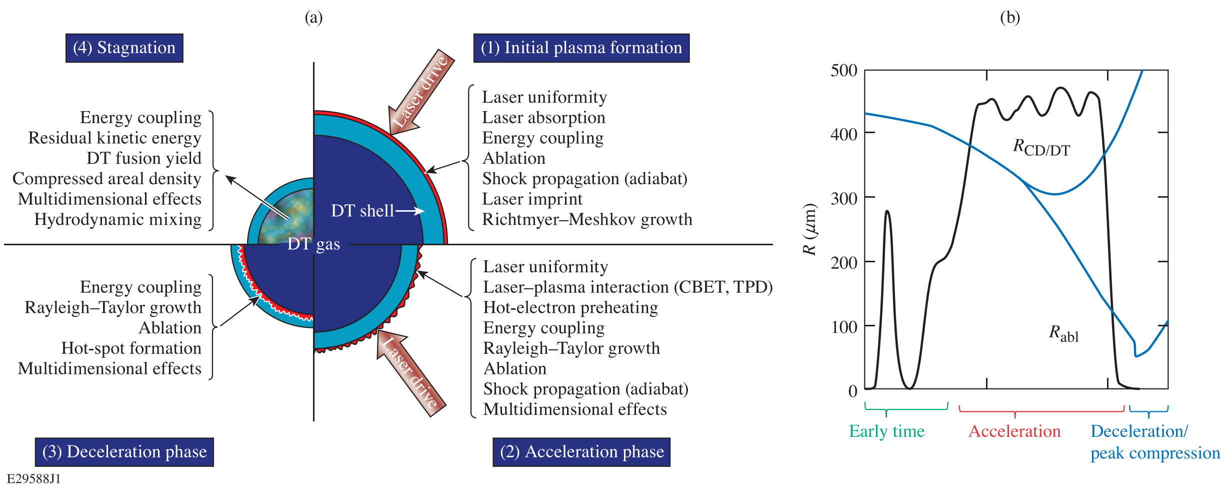

Fig. 6 (Left panel) The four stages of the laser direct drive implosion—initial plasma formation, acceleration, deceleration, and stagnation—and associated key target physics areas. The peak neutron production occurs at stagnation. (Right panel) The time history of the laser power (black curve) and the trajectory of the ablation surface of the imploding shell R_{abl} (lower blue curve) and the trajectory of the ablated CD/DT interface $R_{CD/DT}$ (upper blue curve).

can cause suprathermal electron generation, which has the detrimental effect of preheating the DT fuel and raising the adiabat (Rosenberg et al., 2018; Solodov et al., 2020; Tikhonchuk, 2021). Deviations from a spherical implosion or multidimensional effects can be caused by hydrodynamic instabilities and laser-plasma instabilities. The key target physics during the acceleration phase are laser uniformity, laser-plasma interactions, hot-electron preheating, energy coupling, Rayleigh-Taylor hydrodynamic instability, ablation, shock propagation, and multidimensional effects.

The displacement work that the converging DT shell performs on the nascent hot-spot plasma increases the hot-spot pressure and causes the DT shell to decelerate (see Fig. 6). The inner wall of the DT shell can become unstable to the Rayleigh-Taylor hydrodynamic instability (Tikhonchuk, 2021). Multidimensional effects are amplified during the deceleration phase and can lead to perturbations to the hot-spot plasma (Woo et al., 2018; Shah et al., 2020; Mannion et al., 2021). The key target physics during the deceleration phase are energy coupling, Rayleigh-Taylor growth, ablation, hot-spot formation, and multidimensional effects. The peak values of DT fusion yield and the compressed areal density can be limited at stagnation by hydrodynamic mixing of the ablator and DT ice layer with the hot-spot plasma at stagnation (see Fig. 6) and incomplete conversion of shell kinetic energy into internal energy of the hot spot due to low-mode asymmetries (Woo et al., 2018; Mannion et al., 2021). The key target physics at stagnation are energy coupling, residual kinetic energy, DT fusion yield, compressed areal density, multidimensional effects, and hydrodynamic mixing.

The performance of a laser direct drive ignition target depends on the implosion symmetry (Woo et al., 2018; Mannion et al., 2021), the hydrodynamic instabilities seeded by laser imprint and target features (e.g., microscopic surface debris, fill tube or stalk) (Igumenshchev et al., 2013), the laser–plasma instabilities in the coronal plasma (Kruer, 2003; Igumenshchev et al., 2010; Igumenshchev et al., 2012; Froula et al., 2012; Randall and Albritton, 1981; Rosenberg et al., 2018; Marozas et al., 2018, b; Kruschwitz et al., 2019; Turnbull et al., 2020a, b; Solodov et al., 2020; Tikhonchuk, 2021), and the fundamental material properties (i.e., equation of state, opacity, and conductivity) (Hu et al., 2011, 2015, 2017, 2018; Ding and Hu, 2017; Campbell, 2021). In the near term, mitigation strategies for laser plasma instabilities include laser (i.e., wavelength detuning) (Marozas et al., 2018a, Marozas et al., 2018b, Kruschwitz et al., 2019, Turnbull et al., 2020a, Turnbull et al., 2020b,) and target solutions (i.e., buried Si layer in ablator) (Solodov et al., 2020) that can be implemented on the National Ignition Facility. In the longer term the Laboratory for Laser Energetics is exploring broadband ultraviolet (351-nm) laser technologies to mitigate laser plasma instabilities (Follett et al., 2018, 2019; Bates et al., 2018) and laser imprint, leading to more stable implosions with a higher fraction of laser energy coupled to the hot spot. Recently, the Laboratory for Laser Energetics has demonstrated a significant breakthrough with a novel efficient broadband tripling scheme ($\Delta\omega/\omega > 1.5\%$, >13 THz) (Dorrer et al., 2020). A staged plan has been devised to develop this new laser technology over the next few years for laser direct drive as well as laser indirect drive (Campbell, 2021).

As mentioned in the introduction laser and target upgrades are required on the National Ignition Facility to perform high convergence (CR $>$ 15) polar-direct-drive implosions. The current laser-direct-drive research strategy for estimating the performance scaling from OMEGA to the National Ignition Facility in the absence of these upgrades starts from the theoretical scaling to the NIF, positing the same core conditions achieved on OMEGA can be reproduced at the NIF scale (i.e., the same pressure and scaled density and temperature) (Campbell, 2021). This scaling approximates conservatively that engineering target features (e.g., the stalk or the fill tube) and target-fabrication imperfections that degrade the implosion, scale with size. The impact of all the sources of degradation, including energy coupling, hot-electron preheat, target imperfections, and laser-drive asymmetry, expected at the National Ignition Facility scale are assessed and evaluated through dedicated laser plasma interaction and hydrodynamic experiments on the National Ignition Facility and OMEGA. A comparison of polar direct drive and spherical direct drive laser-irradiation geometries on OMEGA is investigated. The design parameter space available for the laser direct drive approach is determined, and the hydrodynamic scaling is verified within the energy range accessible to the OMEGA laser.

The performance of laser-direct-drive implosions on OMEGA that are hydrodynamically-scaled to the 2.0 MJ of laser energy on the National Ignition Facility assuming spherical direct drive (Goncharov et al., 2014; Regan et al., 2016; Bose et al., 2016; Gopalaswamy et al., 2019; Campbell, 2021; Campbell et al., 2021) were evaluated. The best performing hydrodynamically-scaled, spherical direct drive implosions are predicted to achieve a threefold amplification in fusion yield due to alpha heating, corresponding to a total fusion yield of 0.6 MJ of fusion yield (Gopalaswamy et al., 2019; Campbell, 2021). The energy-scaled, generalized Lawson ignition parameter (Bose et al., 2016) for laser direct drive implosions on OMEGA is approximately 0.75 (Campbell, 2021) A statistical approach was used to design and quantitatively predict the results of the highest-performing laser-direct-drive implosion on OMEGA, leading to tripling of the fusion yield (Gopalaswamy et al., 2019).

A 10-year plan with four physics goals is being developed to implement upgrades to the National Ignition Facility to optimize the performance of polar direct drive DT cryogenic implosion targets in the burning-plasma regime, and to understand the laser facility and target requirements (i.e., energy, power, size, beam smoothing, phase plates, and wavelength detuning) needed to achieve ignition and multi-MJ yield. The first physics goal is to optimize the symmetry of convergence ratio ≤ 10, polar direct drive implosions of room-temperature DT-filled capsules using the current NIF capability and innovative target designs with a goal of achieving a 50-kJ fusion yield. The second physics goal is to improve with modest investment the energy coupling and symmetry for those implosions using wavelength detuning with beam remapping and dedicated polar direct drive phase plates. The third and fourth physics goals require significant modifications on the National Ignition Facility, including a laser direct drive cryogenic target-handling system and upgrades in laser beam smoothing, to increase the convergence ratio to 15 and then to 20 with polar direct drive DT cryogenic target implosions in order to achieve an alpha burner and to reach the burning-plasma regime (i.e., 1-MJ fusion yield), respectively.

Laser-Indirect-Drive Research

Ignition-scale implosions are being performed on the National Ignition Facility using laser indirect drive. As mentioned in the introduction, the challenges with nonuniformities in the laser drive incident on the target surface in the early days of inertial confinement fusion research motivated the development of laser indirect drive (Lindl et al., 1992, 2004; Lindl, 1995, 1998). The laser beams incident on the inner wall of the high-Z hohlraum wall (see right panel of Fig. 2) create an ablation plasma, which converts the laser energy to the x-ray drive (Lindl, 1998). Many of the target physics areas described in the Laser-Direct-Drive Research section are common to Laser-Indirect-Drive Research; however, there are important distinctions related to radiation hydrodynamics of the hohlraum (Lindl, 1998; Barrios et al., 2018, Callahan et al., 2018, 2020; Tikhonchuk, 2021), laser plasma interactions within the hohlraum (Glenzer et al., 2010; Kritcher et al., 2018; Callahan et al., 2020; Tikhonchuk, 2021), conversion of laser energy to shell kinetic energy (Lindl, 1998; Tikhonchuk, 2021), and the seeds of hydrodynamic instabilities (Barrios et al. 2013; Nagel et al., 2015; MacPhee et al., 2017; Martinez et al., 2017; Hammel et al., 2016, 2018; Tikhonchuk, 2021).

Two of the main design considerations for the hohlraum radiation hydrodynamics are the expansion of the high-Z ablation plasma into the hohlraum and the plasma conditions in the laser entrance hole region of the hohlraum, which can adversely affect the laser to x-ray energy coupling and the implosion symmetry (Glenzer et al., 2010; Barrios et al., 2018; Kritcher et al., 2018; Callahan et al., 2018, 2020; Tikhonchuk, 2021). The hohlraum is filled with a low-Z gas, which is ionized by the lasers forming a plasma that tamps the expansion of the high-Z ablation plasma. Target design considerations are made to optimize the energy coupling and implosion symmetry, while mitigating the laser plasma interactions in the hohlraum. Because of the area ratio of the capsule to the inner wall of the hohlraum, approximately 10% of the laser energy is converted to X rays in a hohlraum that are incident on the implosion capsule. The X rays deposit their energy close to the ablation surface of the implosion capsule, which increases the hydrodynamic efficiency of converting the absorbed X-ray energy to inward kinetic energy of the shell via the rocket effect to about 15% versus 9% for laser direct drive. This gives a conversion efficiency of laser energy to shell kinetic energy of about 1.5% for laser indirect drive versus 6% for laser direct drive. Consequently, laser indirect drive solves the laser imprint problem at a cost of lowering the conversion efficiency of laser energy to shell kinetic energy. Initiatives to increase the energy coupling to the capsule are explored using innovative hohlraum designs (Amendt et al., 2019) and increasing the size of the capsule, while keeping the size of the hohlraum fixed (Callahan et al., 2018, 2020). However, these initiatives will only lead to a modest increase in the energy coupling.

Over the last decade the primary neutron yield for laser indirect drive implosions on the National Ignition Facility has been increased from 2×10^{14} to 2×10^{16} (Moses et al., 2009; Glenzer et al., 2010; Meezan et al., 2010, 2015; Michel et al., 2010; Haan et al., 2011; Edwards et al., 2011, 2013; Landen et al., 2011, 2021; Hurricane et al., 2014; Le Pape et al., 2018, Hurricane et al., 2019a, b, 2021; Landen et al., 2020; Patel et al., 2020; Town, 2020; Zylstra et al., 2021). After an initial series of implosions on the National Ignition Facility, where the DT fuel was diluted with hydrogen (H) to reduce the yield (i.e., THD implosions), low-adiabat ignition designs having predicted yields around 3.6×10^{17} or greater than 1 MJ of fusion yield were explored (Haan et al., 2011). When the high neutron yields were not realized in the laboratory, a more phased approach using higher-adiabat implosion designs was undertaken to understand the implosion results (Hurricane et al., 2014). Using the higher-adiabat implosion, that is less susceptible to hydrodynamic instabilities, driven with a low-fill density hohlraums, that have lower levels of laser plasma interactions, alpha heating was demonstrated and burning plasma is now being explored on the National Ignition Facility with laser indirect drive. The highest yield published to date corresponds to 56 kJ of thermonuclear fusion energy, where alpha heating has boosted the fusion yield by a factor of three from that caused by the implosion system alone (Town, 2020; Patel et al., 2020). The generalized Lawson ignition parameter for laser indirect drive implosions on the National Ignition Facility is 0.75 (Patel et al., 2020).

The current hypothesis is the performance of the current laser indirect drive implosions on the National Ignition Facility is limited by the low amount of energy coupled to the hot-spot plasma and two physical degradation mechanisms (Town, 2020). The mode-1 asymmetry caused by the laser imbalance or capsule nonuniformities (Rinderknecht et al., 2020; Casey et al., 2021) and hydrodynamic instabilities seeded by engineering features such as the fill tube (Hammel et al., 2011; Regan et al., 2013; Ma et al., 2013; Pak et al., 2020), capsule support (Nagel et al., 2015; MacPhee et al., 2017; Hammel et al, 2016, 2018; Martinez et al., 2017), and capsule imperfections (Barrios et al., 2013; Town, 2020). This hypothesis is based on the current understanding of experimental results and modeling of alpha heating (Zylstra and Hurricane, 2019; Patel et al., 2020), hohlraum performance (Hall et al., 2017; Kritcher et al., 2018; Callahan et al., 2018, 2020), laser plasma interactions (Kruer, 2003; Regan et al., 2010; Glenzer et al., 2010; Dewald et al., 2016; Kritcher et al., 2018; Callahan et al., 2018; Callahan et al., 2020; Tikhonchuk, 2021), low-mode asymmetry (Kritcher et al., 2014, 2018; Rinderknecht et al., 2020; Casey et al., 2021), engineering feature such as fill tubes, capsule support, capsule quality (Martinez et al., 2017), and the quality of the DT cryogenic fuel layer (Gibson et al., 2009; Johal et al., 2009), low compression (Landen et al., 2020, 2021), implosion reproducibility (Town, 2020).

The thrust of the research over the next five years for laser indirect drive on the National Ignition Facility will concentrate on the following: (1) increasing amount of laser energy coupled to the implosion capsule (Amendt et al., 2019); (2) optimizing implosion symmetry (Callahan et al., 2018; Callahan et al., 2020); (3) mitigating hydrodynamic mixing of material into the hot-spot plasma; (4) increasing the convergence ratio of the implosion and the compressed fuel density (Landen et al., 2020, 2021); (5) improving predictive capability of implosion performance (Marinak et al., 2001; Clark et al., 2011, 2017, 2019a, b; Callahan et al., 2018, 2020; Gaffney et al., 2018, 2019); (6) increasing the energy and power of the National Ignition Facility (Town, 2020).

Ignition is a grand research challenge. Estimates for the amount of laser energy needed on the National Ignition Facility path forward to ignition with laser indirect drive on the National Ignition Facility range from 1.5 times the current 2 MJ of available laser energy, if lower-adiabat implosion with higher energy coupling are viable, to 10 times the current 2 MJ of available laser energy, if no improvements are made to the current implosions (Town, 2020). Understanding the science and improvements in target fabrication with systematic experiments over the next several years will reduce the uncertainty in required driver energy and increase the fusion performance at the National Ignition Facility. Although incremental improvements to the performance are ongoing, understanding predictable ignition is crucial for the laser-driven inertial confinement fusion research.

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