ADVANCED LASER CONCEPTS AND TECHNOLOGIES FOR LASER DIRECT-DRIVE INERTIAL FUSION ENERGY (LDD-IFE)

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Submitted to the IFE Science & Technology Community Strategic Planning Workshop, under the topic Drivers (including driver-specific technologies, e.g., final optics) along with related white papers submitted by the following first authors:

- Inertial Fusion Energy Target Designs with Advanced Laser Technologies (V. Goncharov)
- Shock Ignition: High Gain Target Performance for Inertial Fusion Energy (K. Anderson)
- An automated IFE Target Factory based the “Lab-on-Chip” format (D. Harding)
- Enabling Advanced Ablator Materials for High-Gain Inertial Fusion Energy (IFE) Target Design (S. Hu)
- Fuel Cycle for an Inertial Fusion Energy Reactor: Isotope Separation and Breeder Blankets (W. Shmayda)
- Accelerating the science, technology, and workforce base for inertial fusion energy with a proposed high repetition rate facility (P. Heuer)
- Machine Learning Driven Design Optimization for IFE on Intermediate Rep-Rated Facilities, V. Gopalaswamy

Advanced Laser Concepts and Technologies for Laser Direct-Drive Inertial Fusion Energy (LDD-IFE)

1. Executive Summary – Laser direct-drive inertial fusion energy (LDD-IFE) promises high-gain performance for commercial power production that can leverage years of laser direct-drive inertial confinement fusion (LDD-ICF) research and extend existing laser and target technologies. This white paper presents a comprehensive strategy for developing advanced laser concepts and technologies for LDD-IFE along with other related white papers noted on the cover page.

2. Introduction – LDD-ICF with hot-spot ignition or shock ignition promises the ability to deliver five to six times higher laser energy coupling for imploding capsules than x-ray indirect drive schemes [4,5]. LDD offers a clear path to produce higher ICF yields for a given laser energy, or more modest ICF yields using smaller laser facilities. These advantages along with other features, like advanced target designs suitable for mass production and commercial IFE implementation [1,6], make laser direct-drive inertial fusion energy (LDD-IFE) attractive. Table 1 summarizes notional LDD-IFE point-design parameters that influence laser driver requirements.

Table 1 – hot-spot LDD-IFE notional parameters

Parameter	Value	Refs
Target fusion gain	100	Ref [1,2]
Driver pulse energy	< 1 MJ	
Driver efficiency	≳ 10 %	Ref [3]
Pulse repetition rate	9 Hz	Ref [1,2]
Electrical power output	400 MW	

Laser plasma instabilities (LPIs) pose a challenge to realizing the higher coupling efficiency of LDD [7,8]. Research indicate that broadband laser irradiation can mitigate and even suppress LPI, as well as improve target irradiation uniformity [9,10,11]. Figure 1 shows simulation results that predict UV laser bandwidth $\Delta\omega/\omega \leq 1.5\%$ can mitigate cross-beam energy transfer (CBET) and increase the laser absorption resulting in higher drive pressures, mitigate hot-electron generation at ignition intensities, and eliminate imprint asymptotically within a few picoseconds [10,12,13]. Broadband ultraviolet lasers promise a path to LPI-free and robust LDD-ICF and LDFD-IFE implosions, potentially including shock ignition [14].

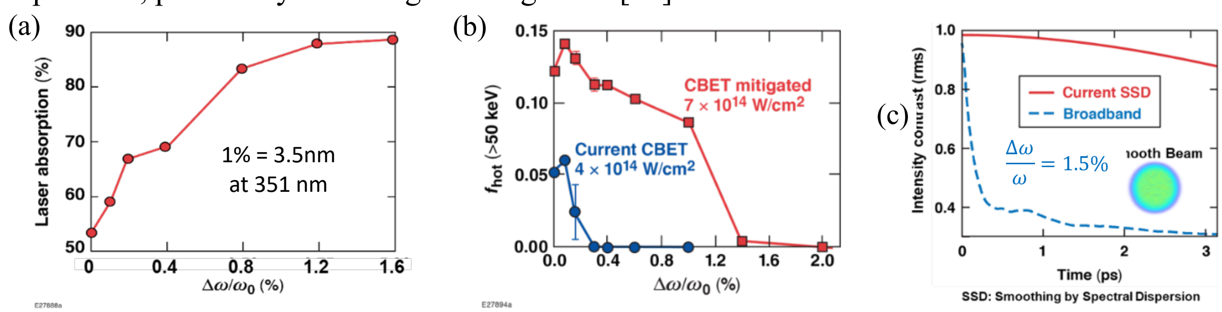

Figure 1: Simulations show laser bandwidth (a) improves laser absorption by mitigating CBET; (b) reduces hot-electron generation that can preheat the capsule; and (c) suppresses focal intensity contrast (beam smoothing reduces laser imprint) on a sub-picosecond time scale, significantly faster than proven smoothing by spectral dispersion (SSD) systems on existing facilities [15,16].

Current ICF laser state-of-art – Laser glass gain and frequency tripling limit the bandwidth required for LPI mitigation and beam smoothing on current ICF lasers, such as the National Ignition Facility (NIF [17]) and OMEGA [18]. These single-shot, basic research facilities employ large-aperture, solid-state laser beamlines pumped with flash lamps. IFE laser drivers will require much higher wall-plug efficiency that can be achieved with diode laser pumping and broad laser bandwidth to achieve the critical IFE metric (driver efficiency × target gain), respectively, that determines the usable output power and recirculating power fraction [2**Error! Bookmark not defined.**]. Two novel concepts described below offer different approaches to overcome technical challenges suffered by existing laser technologies and facilities and extend significantly laser bandwidth delivered for LDD-IFE schemes to achieve high target gain.

3. LDD-IFE technical issues – Several approaches exist to deliver the **bandwidth required for LPI suppression and irradiation uniformity**. Each laser source might produce the full required bandwidth, portions of the bandwidth, or discrete wavelengths spanning the required spectrum. Broadband incoherent systems raise laser damage concerns due to temporal modulation resulting from the excess bandwidth, and broadband frequency upconversion to ultraviolet wavelengths proves challenging, so lasers operating at discrete wavelengths should prove simpler and advantageous, though spectral beam combination [19] may be required to deliver all of the laser irradiation to targets given practical constraints on the solid angle available for IFE reactor vessels. OPA- or laser-based systems can provide the required broadband amplification for LDD-IFE.

FLUX: Figure 2(a) illustrates schematically the technology for Fourth-Generation Laser for Ultrabroadband eXperiments (FLUX) [20,21,22] that employs optical parametric amplification (OPA) and sum frequency generation (SFG) to produce broadband, incoherent UV laser pulses from a single aperture. A fiber front end seeds a broadband signal into a noncollinear OPA (NOPA) stage for subsequent collinear OPA (COPA) seeded by the NOPA signal output only. The COPA output signal and idler waves (1ω) both upconvert to the ultraviolet (3ω) using SFG.

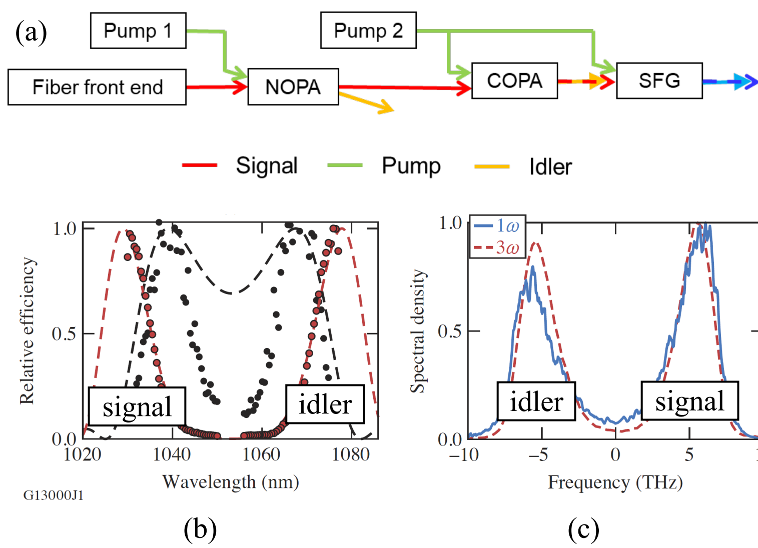

Figure 2: (a) Schematic of conceptual FLUX systems; (b) OPA gain and (c) SFG spectra with symmetric signal and idler bands.

Figure 2(b) illustrates the how collinear OPA can amplify infrared (1ω) signals and produce idler waves with large wavelength differences upconverted by sum frequency generation shown in Fig. 2(c). Both show experimentally demonstrated broadband OPA and SFG results, where different nonlinear tuning produces different bands of signal and idler radiation. An integrated FLUX program underway at LLE [23] will establish an experimental platform on OMEGA to demonstrate broadband LPI mitigation and laser irradiation uniformity improvements with target experiments that will employ the FLUX beam on targets also driven with other OMEGA beams.

StarDriver®: A laser driver system composed of many (10^3 to 10^5) relatively small (cm-scale aperture) beamlines [24] offers another approach to deliver broadband irradiation to direct-drive targets by combining on target the output of lasers operating at many discrete wavelengths spanning the required spectrum. Ideally, incoherent interference of these lasers exists only after the very end of the laser beamlines, which greatly simplifies both laser system design and operation. Smaller apertures open a wider range of gain material options. The modular approach provides scalability across a range of ICF and IFE facilities to enable complex pulse shapes, many wavelengths, and focal spot zooming to optimize LDD drive. The large number of lasers using relatively small, off-the-shelf optical components would spur competitive commercial development leading to economies of scale with high-volume manufacturing that would benefit industrial and other applications for nanosecond lasers of this scale. Diode pumping and active cooling could enable high repetition rates that even reach multi-kHz using proven diode-pumped solid-state laser (DPSSL) architectures [25], as well as new concepts to improve system performance, efficiency, and reliability.

Figure 3 shows the spectral gain ranges of commercial and research-grade laser glasses. Two commercially available laser glass materials, APG-1 phosphate and LG680 silicate, might potentially support $\Delta\lambda/\lambda \sim 2.2$ % bandwidth. Commercially developing others could significantly extend this range. Laser crystalline materials [26,27] might also play a role.

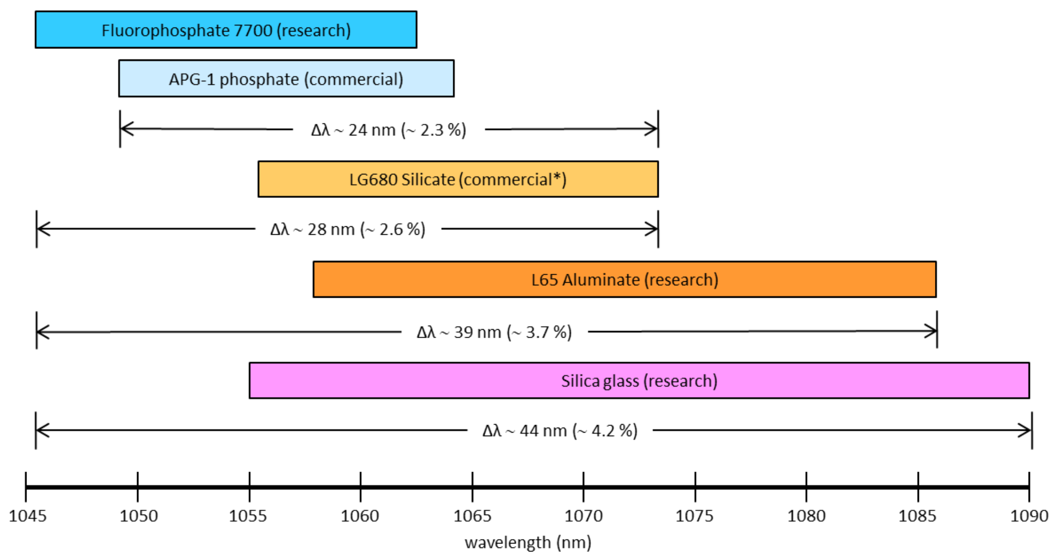

Figure 3: Spectral gain ranges with 70% peak gain of commercial and research-grade laser glasses.

High-gain IFE targets require **high laser-drive uniformity** (< 1% rms) for stable implosions. Uniformity depends on single-beam focal spot uniformity and good power balance across all beams. Active beam smoothing systems implemented on existing facilities [15,16] yield the best focal spot uniformity currently possible for existing solid-state laser systems, but they increase system complexity significantly and only smooth mid- to high-spatial frequency nonuniformities with asymptotic smoothing limited by current laser materials. FLUX and StarDriver® promise significant improvements with much more laser bandwidth leading to faster asymptotic smoothing, as shown in Fig. 1(c). Power balance requires carefully matching beamline output with closed-loop control systems that would employ machine learning to optimize performance.

Focal spot zooming would improve overall LDD drive efficiency by reducing (or eliminating) geometric overfill of the imploding target that leads to deleterious LPI, like CBET [28,29,30]. Figure 4 illustrates conceptual designs for implementation at two important scales: an OMEGA-like facility that could demonstrate LPI-free LDD-ICF, and a laser driver suitable for a high-gain IFE facility. Dividing the laser drive amongst subapertures that each combine multiple sources of narrowband radiation offers significant advantages for realizing practical IFE laser systems by optimizing each source for a particular wavelength, pulse shape and focal spot during the implosion.

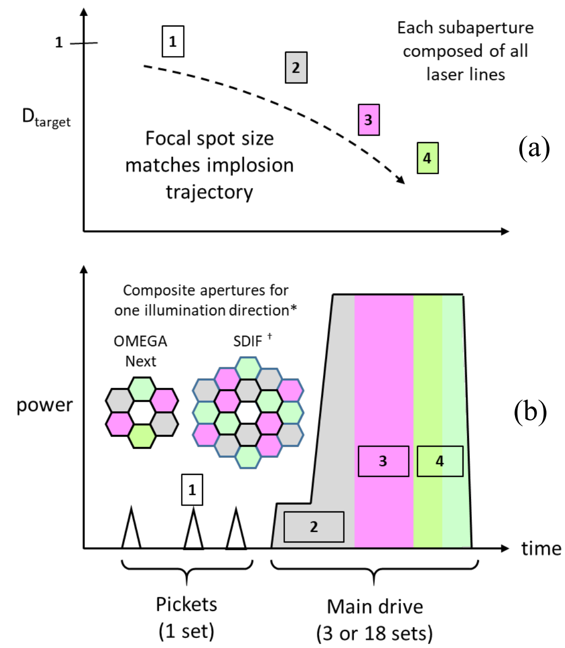

Figure 4: StarDriver® notional concept with composite pulse shaping and apertures to deliver many lasers in a direct-drive configuration.

Figure 4(a) illustrates four different laser spot sizes on target that stepwise match an imploding LDD target and Fig. 4(b) presents the corresponding ignition pulse shape with pickets composed by stitching together pulse shape segments. The inset of Fig. 4(b) shows the corresponding subapertures with the same color-coding: one for a 30-kJ OMEGA-like facility with seven subapertures and another for a 1-MJ StarDriver® IFE Facility (SDIF) facility with 19 subapertures. Each composite aperture illuminates one of 60 directions in a spherically symmetric OMEGA drive configuration. Each subaperture beam combines ~10 discrete laser lines to deliver full bandwidth during each segment of the implosion with a corresponding phase plate that sets the spot size on target. A notional OMEGA-like facility based on the StarDriver® concept would have ~2,400 lasers each delivering ~10 to 20 J (UV) in ~4-cm diameter beams; a SDIF would comprise ~18,000, ~60-J UV lasers with ~6-cm diameter beams.

Repetition rate/average power – IFE will require continuous operation at approximately 10-Hz repetition rate or higher to produce viable commercial power. Direct diode pumping and active cooling have achieved the required laser wall-plug efficiency (~20%) and average powers [31,32]. Feedback control coupled with machine learning at these repetition rates will enable stable operation optimized for IFE power production.

Precision pulse shaping – LDD-IFE requires precise pulse shaping to achieve the required high-gain implosions. Modern arbitrary waveform generator (AWG) technology coupled with scalable architectures [33], closed-loop feedback, machine learning, and can provide the precision and flexibility required to adapt to variations of IFE operating conditions.

4. Research and development (R&D) needs and opportunities – Three areas of early laser R&D can advance LDD-IFE technology as part of a technology maturation plan [34] and prepare for IFE commercialization: (1) system design and optimization studies, (2) leveraging advanced DPSSL technology to build and test a prototype laser module, and (3) commercial development of laser gain materials. All three areas can and should proceed in parallel closely coupled with other LDD-IFE R&D to converge on an integrated solution. The R&D will involve university and industrial partners to leverage their unique capabilities, plus establish a natural channel for maturing the laser technology from concept through demonstration to production and operation.

4.1 Develop IFE laser system architecture/conceptual design options and optimize system performance. LDD-IFE laser designs can leverage and extend existing DPSSL technology, but the broadband requirements depend on defining a suitable system architecture that can optimize IFE performance. Proposed LDD-ICF experimental studies using a high-energy HED facility [35] operating at higher shot rates (shot/min), and simulations of both hot-spot and shock ignition target designs [1,6] would support these design efforts. System studies and research would explore the optimal number of sources/subapertures/illumination directions for an IFE reactor. Design and optimization studies would:

- Develop IFE laser system architecture and conceptual designs, including but not limited to FLUX, StarDriver®, and hybrid FLUX-StarDriver®.
- Perform system analyses and optimize performance of designs with simulations [1,6] benchmarked by results from LDD-ICF experiments [35].
- Down select a laser architecture and develop an LDD-IFE driver preliminary design.

4.2 Design and build a prototype DPSSL module. Directly diode-pumped lasers represent the most mature technology suitable for LDD-IFE, but it requires advancing the technology readiness of high-average-power *and* high-energy lasers for any laser architecture selected in 4.1. Advanced DPSSL technology exists from R&D driven by scientific, industrial, and military applications [25,31,32] that can be leveraged and extended to demonstrate a prototype IFE laser module in an IFE laser testbed. This program would raise the technology readiness level (TRL) to prepare for commercial IFE deployment. DPSSLs developed at General Atomics under the HELSI program [25] look particularly promising as a potential starting point, since they have evolved through eight generations to TRL5. The current generation represents the state-of-the art for high-average-power lasers with a form factor well suited for an IFE laser module. A comprehensive prototype DPSSL module design and experimental program would:

- Evaluate existing DPSSL concepts, identify pros/cons, assess TRLs, and down select.
- Develop laser conceptual, preliminary, and final designs that can demonstrate performance at different operating wavelengths using existing and newly developed laser gain materials (laser and/or FLUX with narrowband signal-idler pairs).
- Build and test breadboard/brassboard IFE DPSSL platform in laboratory. (TRL4 to TRL5)
- Develop conceptual and final designs for production-scalable IFE module.
- Build and test prototype DPSSL laser module to demonstrate laser performance, as well as used for damage/lifetime studies of optics, and controls development. (TRL6 to TRL7)

4.3 Develop new laser gain materials suitable for StarDriver® DPSSLs. Broadband LDD-IFE drivers based on laser amplification require laser materials R&D to support the needed bandwidth. A single laser gain material does not exist at this point, so several will be needed. Research-grade laser glasses shown in Fig. 3 show promise but they require R&D to verify their suitability and to develop commercial production processes. Novel crystalline materials, such as $Nd:CaF_2$ co-doped with laser inactive rare-earth ions [**Error! Bookmark not defined.**] and/or ceramic laser materials [36,37] may also offer potentially attractive options. The relatively small apertures required should broaden the range of materials to consider. A comprehensive laser materials development program would:

- Review literature results and perform experiments to characterize laser, optical, and material properties of existing research-grade laser glass and crystal samples.
- Identify and prioritize materials on which to focus production process development.
- Develop production processes for prioritized materials. (TRL4)
- Produce prototype laser materials for characterization and laser demonstrations (TRL5).
- Produce laser materials for prototype DPPSL module (TRL6 to TRL7).

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