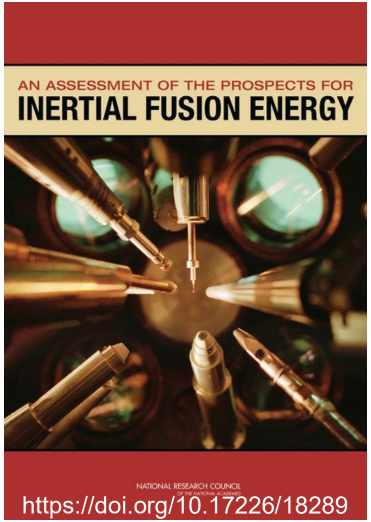
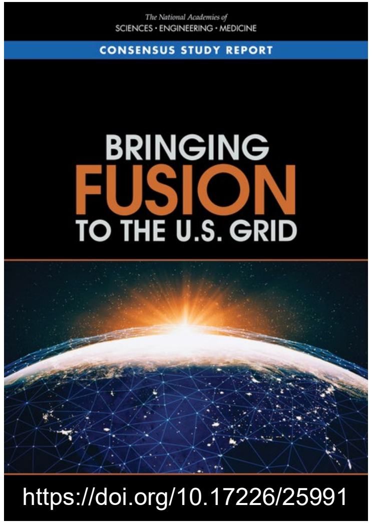
Diode-pumped, solid-state laser (DPSSL) drivers for Inertial Fusion Energy (IFE)

National Research Council (2013)



NASEM (2021)



Fast Forward

NIF Shot N210808
August 2021

DOE-FES
Basic Research Needs (BRN) Workshop
May 2022

NIF Shot N221205
December 2022

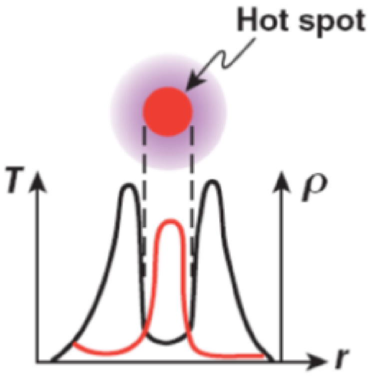
Jon Zuegel
Division Director, Laser & Materials Technology
Professor of Optics
University of Rochester

Enabling Technologies for Improving Fusion Power Plant Performance and Availability Workshop, New Orleans, LA
March 7, 2023

The difference between conventional "hot-spot" and two-step ("fast" or "shock") ignition is similar to that between a diesel and gasoline engine

UR LLE

Hot-Spot Ignition

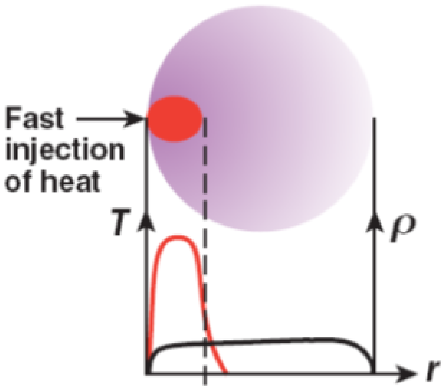


Low-density central spot ignites a high-density cold shell

$\rho T_{hot} \approx \rho T_{cold}$ (isobaric)

Laser Indirect Drive (LID)
or
Laser Direct Drive (LDD)

Fast Ignition

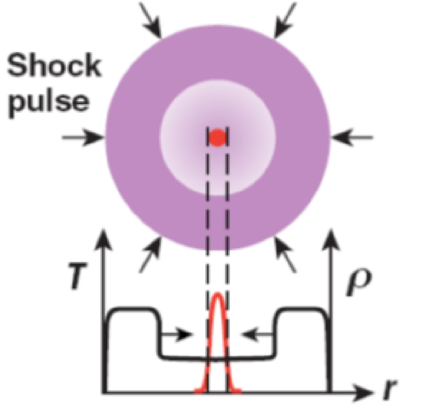


Fast-heated side spot ignites a high-density fuel ball

$\rho_{hot} \approx \rho_{cold}$ (isochoric)

Laser Direct Drive (LDD)
maybe
Laser Indirect Drive (LID)

Shock Ignition



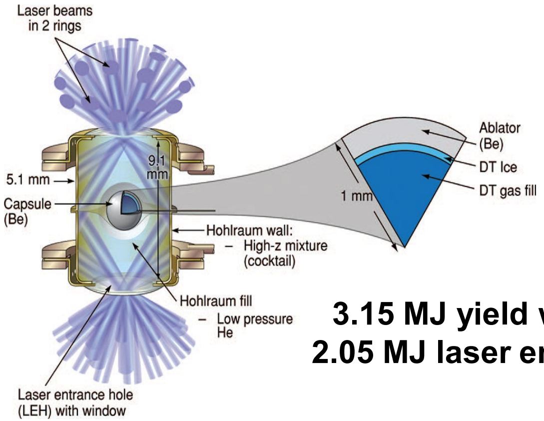
Spherical shock wave ignites a high-density fuel ball

$\rho T_{hot} \gg \rho T_{cold}$

Laser Direct Drive (LDD)

NIF demonstrated hot-spot ignition using laser indirect drive, and OMEGA recently demonstrated hot-spot gain >1

Laser Indirect Drive (LID)

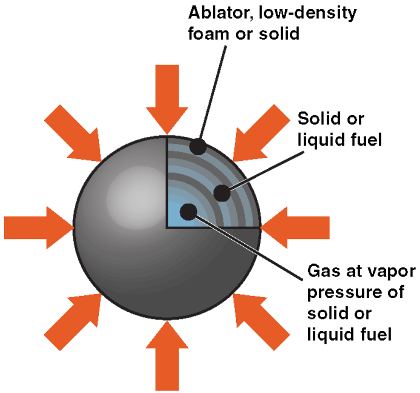


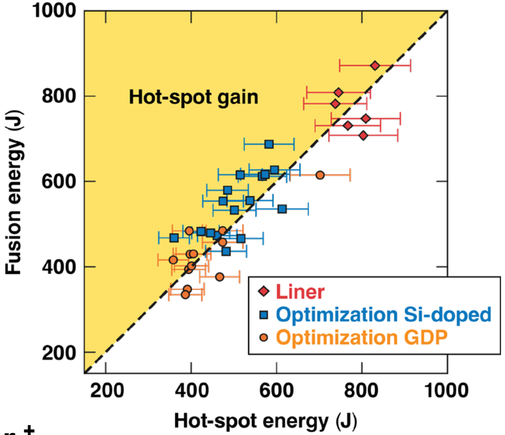
3.15 MJ yield with
2.05 MJ laser energy

National Ignition Facility *

- ~ 2 MJ (UV)
- 192 (~40×40 cm^2) beams in 48 quads
- polar-drive configuration
- ~ 1 shot per 8 hours

Laser Direct Drive (LDD)





OMEGA-60 Laser †

- ~ 30kJ (UV)
- 60 beams (~30-cm diam.)
- spherical-drive configuration
- ~ 1 shot per hour

1-2 MJ laser drive
will produce higher
target gains than LID

* Haynam, Appl. Optics (2007) † Boehly, Opt. Commun. (1997)

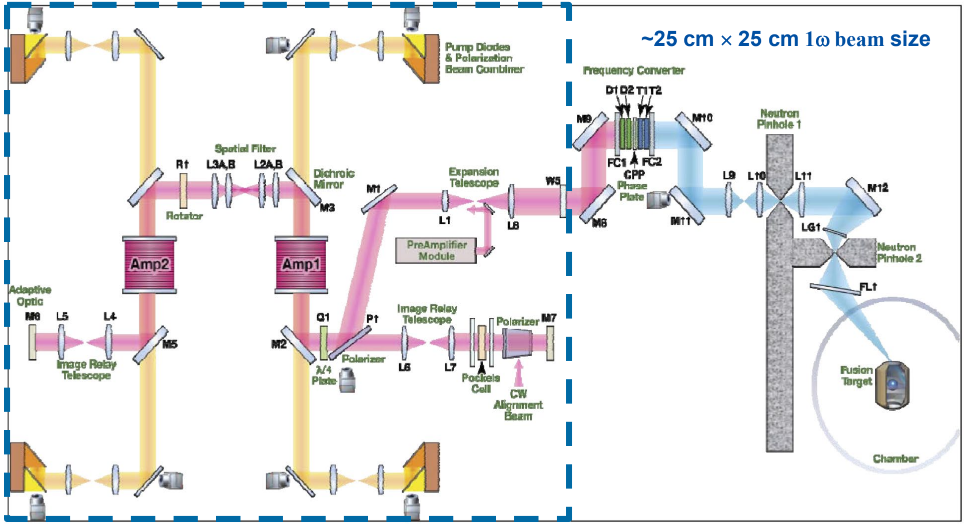
Top-level requirements for IFE solid-state laser drivers

- **IFE laser-driver requirements:**

Energy:	compression:	MJ-class with many (100s to 1000s) beamlines
	fast ignition:	10-150 kJ with multiple beamlines
Wall-plug efficiency:	$\geq$ 10% [higher is better!]	
Capital costs:	"competitive" [Overnight Capital Cost (OCC) and Levelized Cost of Electricity (LCOE)]	
Repetition rate:	~ 1-10^+ Hz [depends on target yield, requires diode pumping]	
Wavelength:	compression:	near UV [~1/3 μm, possibly 1/2 μm]
	fast ignition:	near IR [~1 μm]
Pulse length:	compression:	nanoseconds
	fast ignition:	picoseconds
	athermal:	femtoseconds
Temporal pulse shaping:	high precision (~1%) and high dynamic range (~100:1)	
Bandwidth/tunability:	depends on IFE approach [bandwidth expands design space for *all* approaches]	
Focal spot uniformity:	depends on IFE approach [LDD benefits from zooming]	
Service Lifetime (MTTF):	Gigashots (1 year @ 10 Hz = 315,360,000 shots!)	

The Laser Inertial Fusion Energy (LIFE) concept applies diode-pumped, solid-state laser (DPSSL) technology for Laser Indirect Drive (LID)

LIFE* laser architecture



10.5 × 2.2 × 1.35 m³ Line Replaceable Unit (LRU)

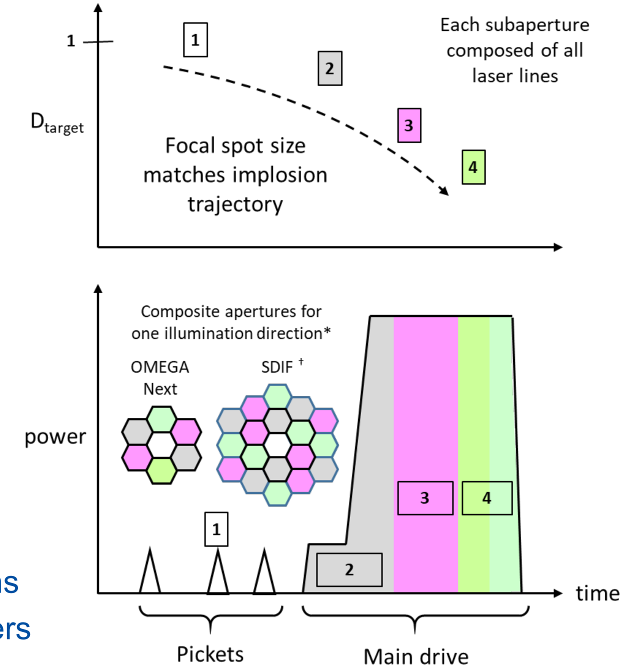
TABLE I. Top level laser system requirements

Characteristic	Requirement
Total laser energy	**2.2 MJ**
Total peak power	**633 TW**
# beamlines	**384 (48 x 8)**
Energy per beamline (3w)	**5.7 kJ**
Wallplug efficiency	**15%**
Repetition rate	**16 Hz**
Lifetime of system	**30 x 10^9 shots**
Availability	**0.99**
Maintenance	**< 8 hrs**
Beam pointing	**100 μm rms**
Beam group energy stability (8 beams)	**<4% rms**
Beam to beam timing at target	**< 30 ps rms**
Focal spot (w/ CPP*), 95% enclose	**3.1 mm**
Spectral bandwidth, 3ω (GHz)**	**180**
Prepulse (20 ns prior to main)	**< 10^8 W/cm²**

* A. Bayramian *et al.*, “Compact, Efficient Laser Systems Required for Laser Inertial Fusion Energy,” Fusion Science and Technology, 60:1, 28-48, (2011); https://doi.org/10.13182/FST10-313

Many relatively moderate-scale beamlines operating at N discrete wavelengths could deliver broadband irradiation to LDD targets to mitigate/suppress LPIs*

- **Modular approach provides scalability** across a range of ICF and IFE facilities and enables composing complex pulse shapes and focal spot zooming to optimize LDD drive
- **Small apertures enable a wider range of gain material options**
- **Off-the-shelf optical components** will spur competitive commercial development and mass production leading to economies of scale and broader supply chains
- **Moderate-scale lasers (100s J to few kJ)** could benefit other markets/applications and enable favorable development pathways
- **Employ proven DPSSL architectures and enable new concepts** to improve system performance, efficiency, and reliability.
  - StarDriver* requires up to N different optimized IFE DPSSL designs
  - PolyKrōm† concepts (OPA + DPSSL) reduce the # of required lasers

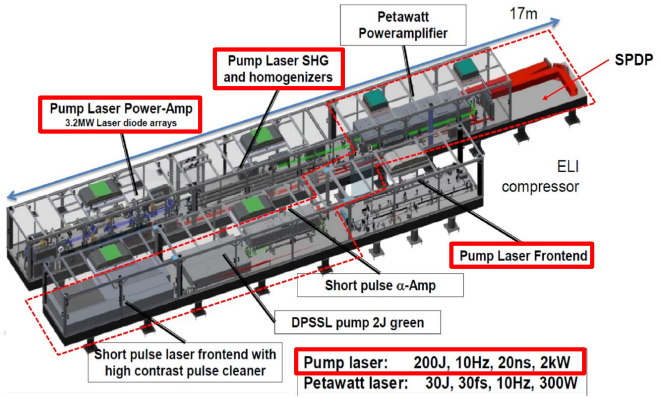


* D. Eimerl *et al.*, "StarDriver: A Flexible Laser Driver for Inertial Confinement Fusion and High Energy Density Physics," J. Fusion Energy vol. 33, pp. 476–488 (2014).

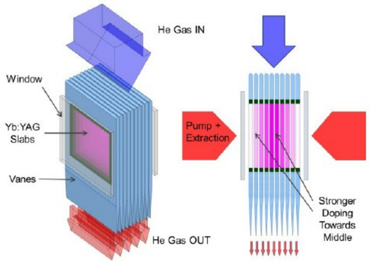
† J. D. Zuegel and C. Dorrer, "PolyKrōm: Two New Broadband Laser Architectures for Laser Direct-Drive Inertial Fusion Energy (LDD-IFE)," IFE white paper submitted to the 2022 IFE Basic Research Needs Workshop, 21–23 June 2022.

The state-of-the-art for high-average-power diode-pumped, solid-state lasers (HAP-DPSSLs) has advanced significantly with some systems already fielded

HAPLS pump laser @ ELI Beamlines

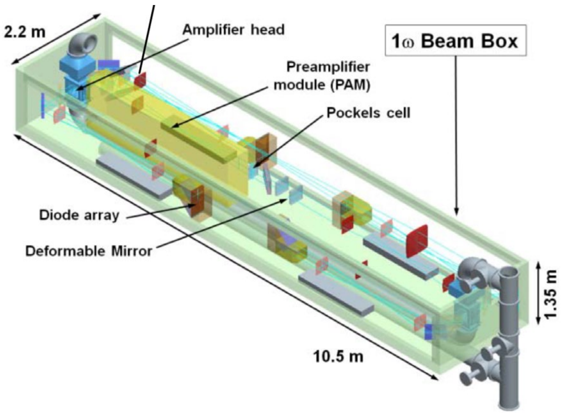


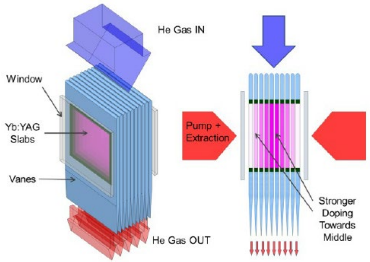
- **Nd:phosphate glass slabs**
- **RT helium gas cooling**



The state-of-the-art for high-average-power diode-pumped, solid-state lasers (HAP-DPSSLs) has advanced significantly with some systems already fielded

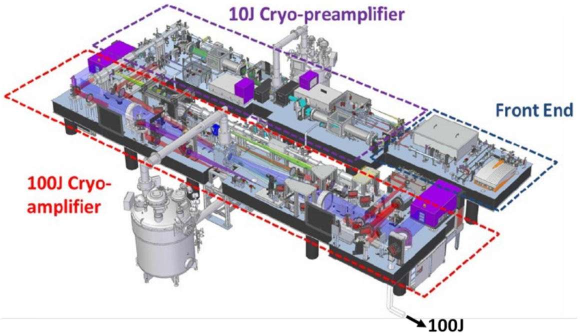
LIFE "Beamline in a Box" Concept





- Nd:phosphate glass slabs
- RT helium gas cooling

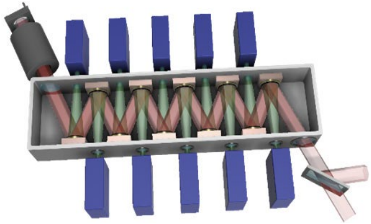
DiPOLE-100X at HIBEF/EuXFEL

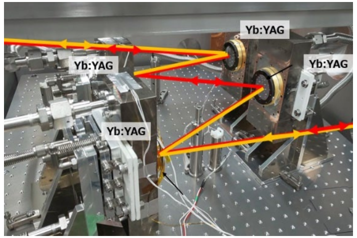


- Yb:YAG ceramic slabs
- cryo helium gas cooling

SENJU

Super-Energetic Joint Unit





- Yb:YAG ceramic active mirrors
- cryo conduction cooling

DOD-funded DPSSL developments ...

IFE BRN Workshop identified Priority Research Opportunities (PROs) for diode-pumped, solid-state laser (DPSSL) drivers

PRO 4-1: Perform IFE driver system-level architecture conceptual design studies [LID + LDD + FI]

- IFE targets, laser tech and architectures, and balance of plant require self-consistent designs with peer review

PRO 4-2: Reduce the cost of diode pumps in DPSSL technologies [LID + LDD + FI]

Boost performance and establish mass production of diode lasers

- Improve electro-optic efficiency at high brightness
- Advance diode reliability and MTTF assurance
- Reduce cost of diode production to US$0.01/Watt
- Standardize + develop multiple sources for pump diodes

PRO 4-3: Increase the damage threshold optics and crystals [LID + LDD + FI]

- Optics and optical coatings with high UV laser-induced damage threshold at high average powers

PRO 4-4: Build integrated laser system demonstrators [LID + LDD + FI]

- Demonstrate compact, industrial-grade laser modules to prove component and control technologies; retire most driver risks for all three primary DPSSL-based approaches (LID, LDD, and LDD with FI)

PRO 4-6: Design systems for broadband lasers [LDD + FI]

- New DPSSL gain materials and nonlinear optics (OPA, frequency conversion, plasma optics)

PRO 4-7: Design and implement final optic survivability at ultra-high intensity [LID + LDD + FI]

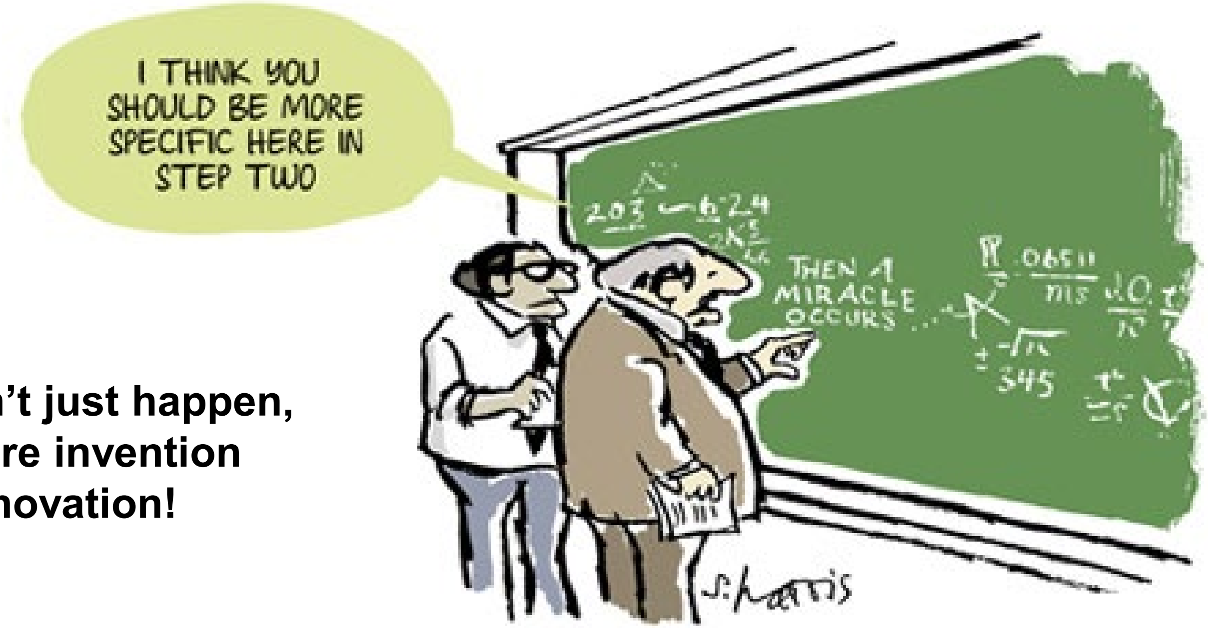
- Fast ignition schemes require large-aperture diffraction gratings and reflective focusing optics

What kind of TRL jumps might be possible?

Near-term: 2-3 years / Mid-term: 3-9 years / Long-term: 10+ years

	Technology	Current state	Technical gaps	Pathway	
TRL5 MRL1	Semiconductor diode lasers	• 500W/bar: human alignment • 1kW bars available but w/ reduced lifetime and ~55% E-O efficiency	• Reduce cost to < \$0.02/W • Lifetime needs to improve > 10x • Improve E-O efficiency to 70%	• Mid-term: Increase to >2kW/bar, E-O to 70% • Long-term: Automate manufacturing, Standardization, Multiple sources	**\$\$ \$\$\$**
TRL4	Laser wall-plug efficiency	• ~5% typical for pulsed lasers • ~16% (unpublished @ 1ω)	• improve extraction and pump-efficiency	• Mid-term: new laser schemes + gain media	**\$\$**
TRL4	3ω Freq. Conv.	KDP w/ high LIDT at 0.1% BW	• KDP linear absorption too high for high-average powers	• Mid-term: new materials (e.g. LBO) • Long-term: larger apertures (if required)	**\$\$**
TRL4	Gain Isolation	Moderate-scale KDP Pockels cells + Faraday isolators	• KDP linear absorption too high • larger apertures (some schemes)	• Mid-term: DKDP and/or FR w/ ppm absorption and depolarization <0.1%	**\$\$**
TRL4	Final focusing	Fused silica 3ω optics	• neutron/gamma-induced damage	• Fresnel/reflective focusing (depends on scheme)	**\$\$**
TRL3	Gratings	~ 1-m scale < 1 J/cm^2 damage threshold	• Higher damage thresholds &/or larger gratings required to deliver FI energy	• Mid-term: scale existing fabrication processes	**\$\$\$**
TRL4	LPI mitigation	STUD pulses for LID	• Complex pulse generation • Physics demonstration	• Mid-term: Front-end laser development and physics demonstration at relevant scale	**\$**
TRL4 TRL3	LPI mitigation	FLUX broadband for LDD	• FLUX concept demo only at small scale	• Near-term: FLUX physics demo on OMEGA • Mid-term: PolyKrōm OPA demo on OMEGA • Long-term: PolyKrōm DPSSL or StarDriver?	**\$ \$\$\$**

Thanks for your attention!



Miracles don't just happen, they require invention and innovation!