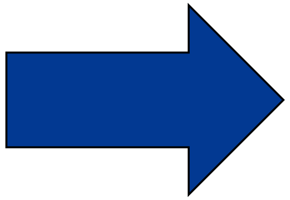
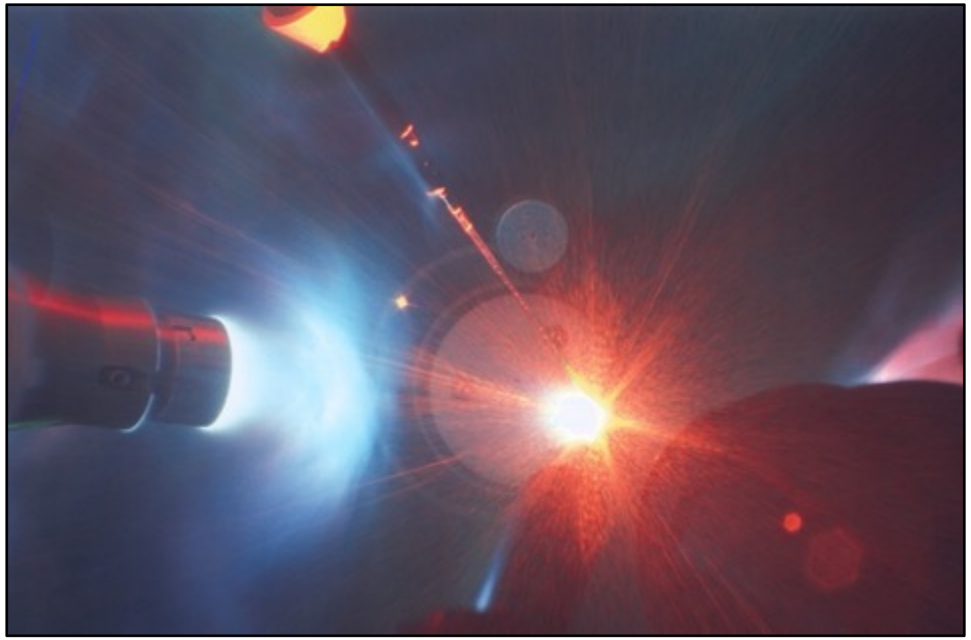
Laser Drivers for Inertial Fusion Energy-Opportunities and Challenges





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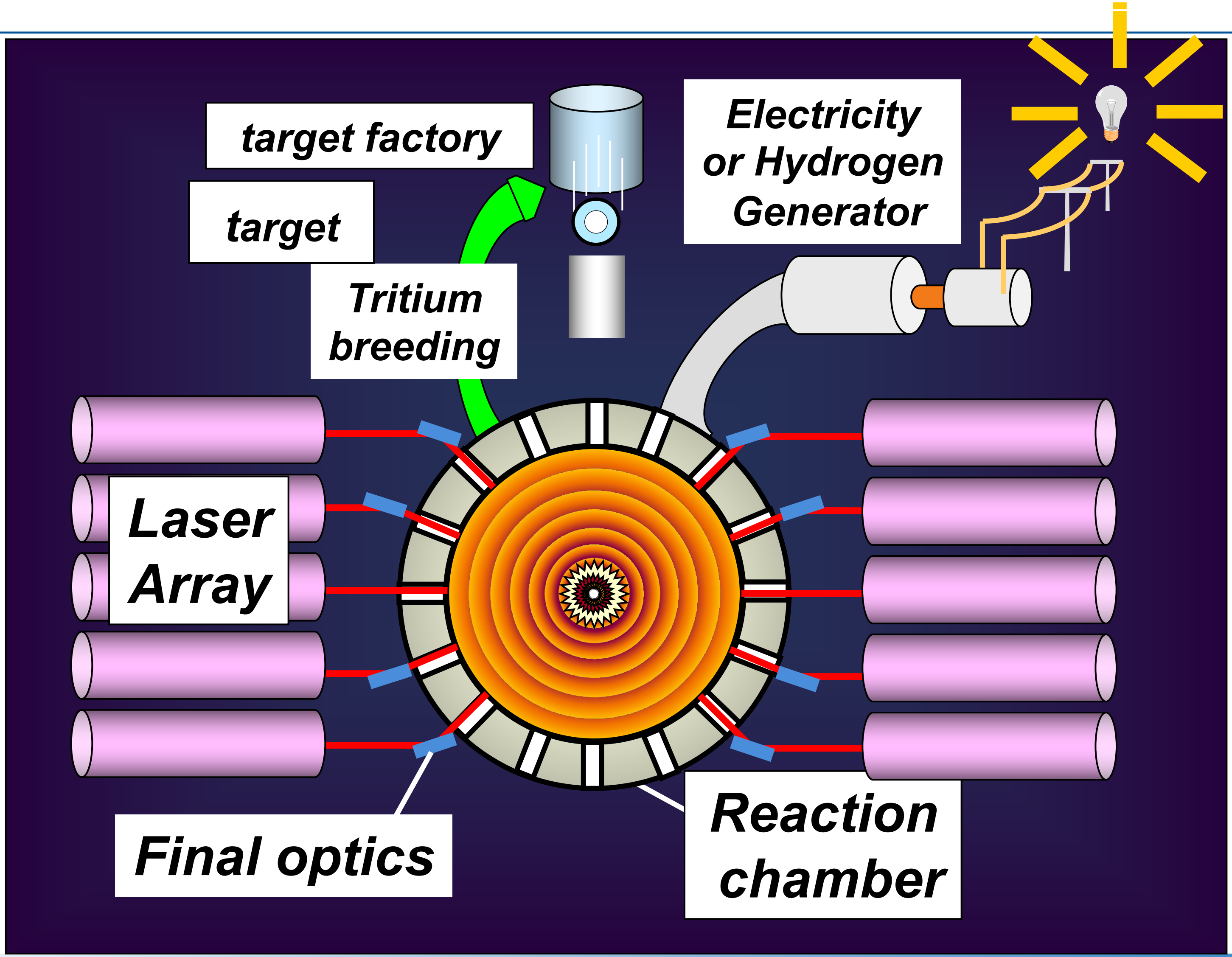
IFAST
April 21, 2022

Fusion energy with lasers requires ηG[1]>~10 for acceptable levels of recirculating power to the plant (DT fuel cycle as an example)



The metric is not G (E_{driver}) but ηG (E_{driver})

[1]Driver efficiency, η; Target gain, G

IFE (DT) features, advantages, challenges

IFE Features:

- Rep rates from 0.1 Hz to 10 Hz
  - 3.16×10^6 -3.16×10^8 /yr (@ 100% capacity factor)
- **Driver**
  - Energy/pulse
    - 0.5-20 MJ
  - Peak power
    - >~500 TW
  - Average power
    - 3 to 10 MW
- Targets
  - ~9,000 to 900,000/day
  - Target cost <$1

IFE advantages

- Separable components
- Highly modular
- Intrinsically safe (NO safety systems)
- Attractive development path
  - "Non-nuclear" demo plant
  - Low rep-rate "nuclear" facility for target development
  - Driver modularity
- Fueling and ash removal
- Load following
- Flexible "first wall"
- Technology and science spin-offs
- Multiple target concepts (same driver)
- Multiple sponsors for technology and science (DOD, NNSA, Industry)
  - Technologies (i.e., laser diodes, optics)
  - Target physics and supporting technologies
  - Scientists and engineers

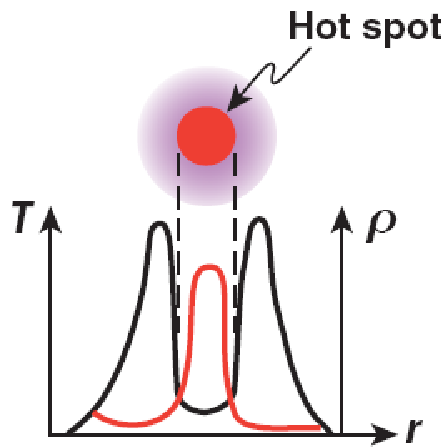
What don't I believe?

To be economically attractive assuming 40% conversion efficiency, each 9 GJ of fusion must cost less than $60 to $100—cost of entire system [target, reactor, Tritium (breeding and recovery), driver, and delivery system].

There are several target concepts for ICF that would be explored in an IFE program

Self-Ignition

Conventional ICF



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

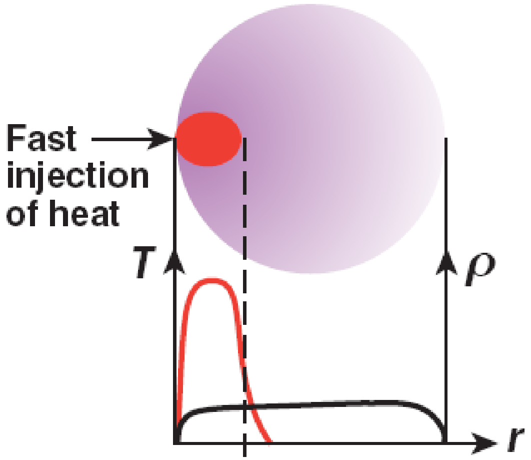
$\rho T_{hot} \approx \rho T_{cold}$ (isobaric)

Features

- Single laser
- I_{peak} ~10^{15} watts/cm^2
- Shaped ~5-10 nsec pulse

External "Spark"

Fast Ignitor



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

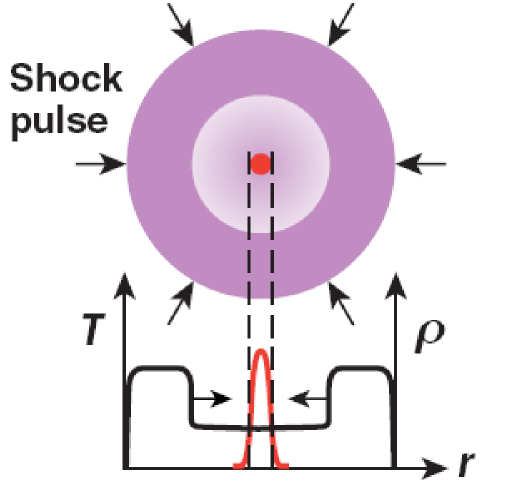
$\rho_{hot} \approx \rho_{cold}$ (isochoric)

Features

- two lasers
  - ~5-10 nsec long pulse, I_{peak}~5 x10^{14} (compression)
  - 1-10 psec, I_{peak}~10^{19} (ignition pulse)

External "Spark"

Shock Ignition



Spherical shock wave ignites a high-density fuel ball

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

Features

- Single laser
- I_{peak} ~10^{16} watts/cm^2
- Shaped ~5-10 nsec pulse followed by intense ~100 psec pulse

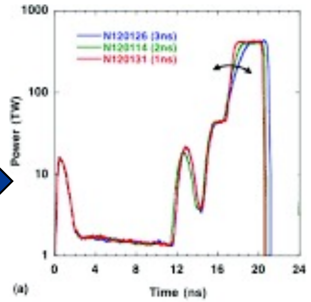
While the demonstration of ignition on NIF is a major scientific achievement and an "existence proof" that central hot spot ignition can be done with modest energy and mass, significant research, engineering and technology development is required for IFE

Capacitor banks (~400 MJ)

Flash lamps

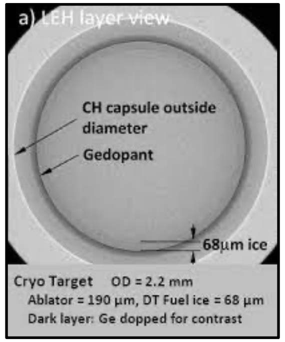
4 to 5 MJ at 1052-nm laser

Frequency conversion



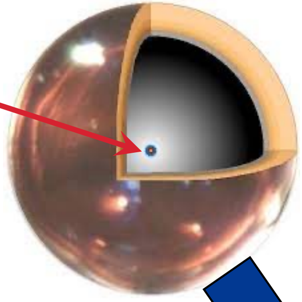
~2 MJ at 350 nm (~0.5% EO Efficiency)

~1.8 MJ at 300 eV blackbody Hohlraum



~0.2- to 0.3-MJ capsule

~0.02 MJ imploded target



1.35 MJ of fusion (capsule Q~6)

A conversation at LLNL in 1960

Edward, I think we can do fusion with this new invention, lasers!

John Nuckolls
("father of ICF")

Not if plasma physics gets in the way!

Edward Teller

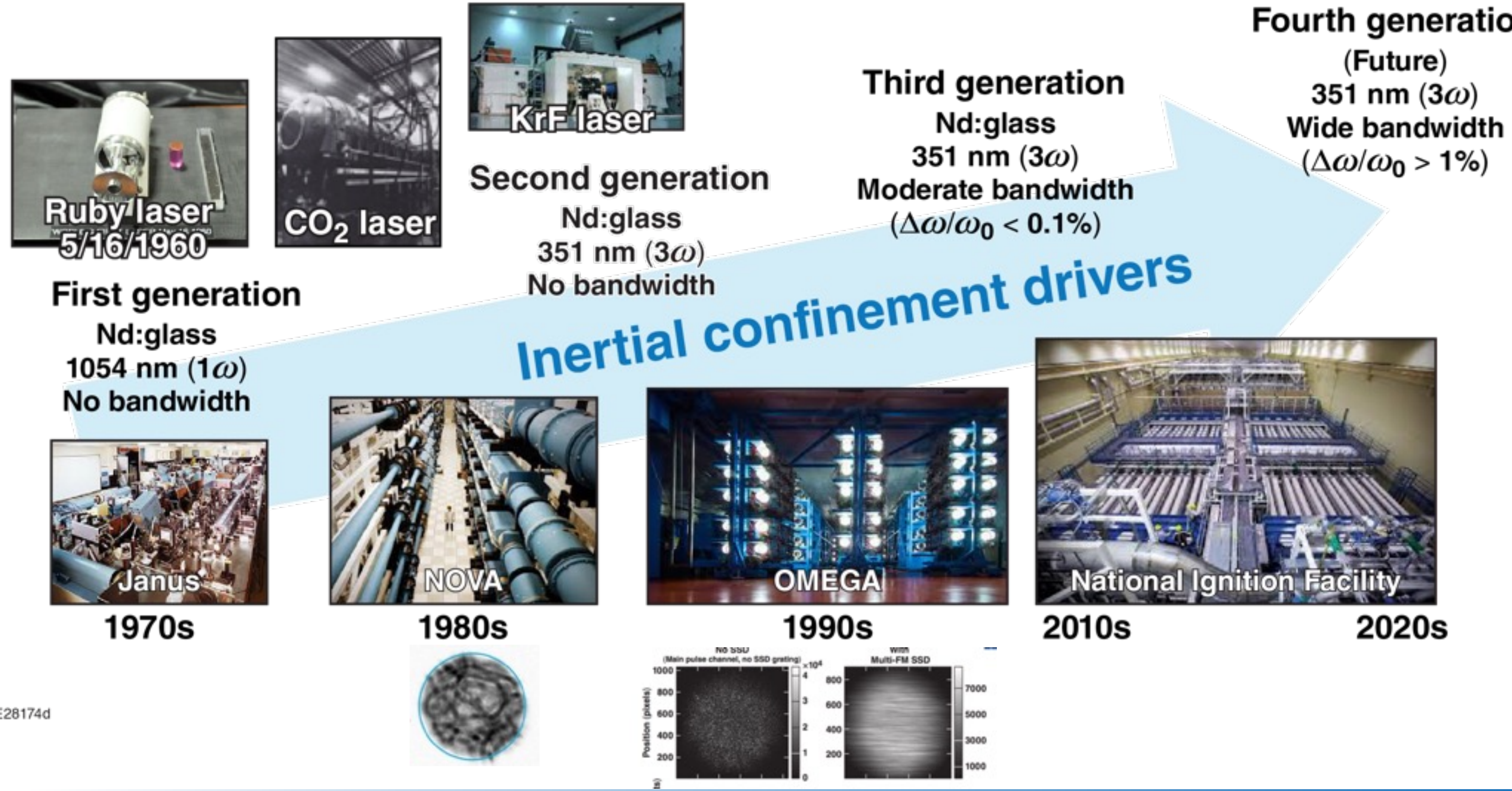
You should be worried!

Marshall Rosenbluth

John Hunt
(Inventor of modern SSL architectures)

Short wavelength, incoherence (Spatial, Temporal), stud pulses are solutions.

Present ICF/HEDP laser drivers are based on S&T developed in the 1980s and 1990s; LPI motivated <u>every</u> generation change in laser drivers: IFE lasers must be ”LPI free”



E28174d

Lasers for IFE

- **Considerations**
  - Must enable Intensity on target required for Ignition and gain (P_{abl}~$(I_{abs})^{2/3}$
    - High absorption, understand laser deposition in space and time, avoid processes that reduce target compressibility
  - Efficiency ("grid to laser" must be such that ηG~>10 where η is laser energy/input energy and G is target gain)
    - Important to consider all energy required for the laser-including thermal management (i.e flow, coolant! This is generally not done)
  - Economics
    - $/Joule to construct
    - Operability and reliability
      - Includes optical train to target
  - Development
    - Supply chain
    - S&T infrastructure
    - "Unit cell" demonstration
    - Other applications for motivation

There are two options for IFE laser drivers: Excimer lasers

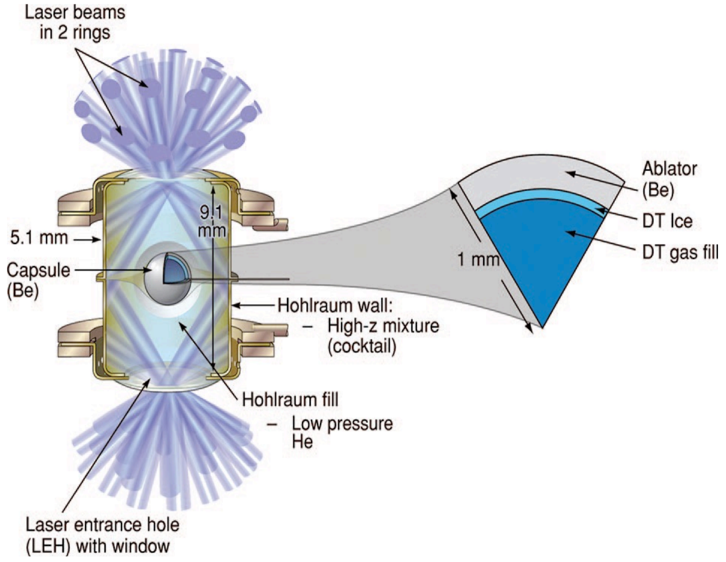
- **Excimer lasers (KrF, ArF): Pulsed power gas lasers**
  - **Advantage**
    - **Short wavelength (krF (248 nm); ArF (193 nm)**
      - **Good target coupling**
    - **Potential for good beam quality on target**
      - **Reduced imprint**
      - **Able to zoom (beam spot follows the implosion increasing the coupling efficiency)**
    - **Gain media is a gas (low cost, low non-linear optics),**
    - **Supply chain motivated by use in lithography**
  - **Challenges**
    - **Small community for high energy (100's of KJ to MJ) applications**
      - **i.e. lithography community is 'discharge laser at <Joule/pulse**
    - **E-O efficiency ~< 10%**
    - **Target concepts limited to conventional "hot spot" or shock ignition**
    - **Short wavelength stresses "laser imprint Issues" (adequate bandwidth (>~10 THz) needs to be evaluated**
    - **High fluence Optical components and transport due to high photon energy (~5 ev) for entire optical train**
    - **High voltage and current pulsed power coupling to gain media**
    - **Short lifetime (nsec) of upper laser state requires "pulse compression techniques to go from microseconds to IFE relevant (~10 nsec) pulse durations**
      - **Compression techniques**
        - Optical multiplexing (NRL)
        - Pulse compression (SBS, SRS) Excimer (bandwidth impact)

There are two options for IFE laser drivers: Solid State lasers

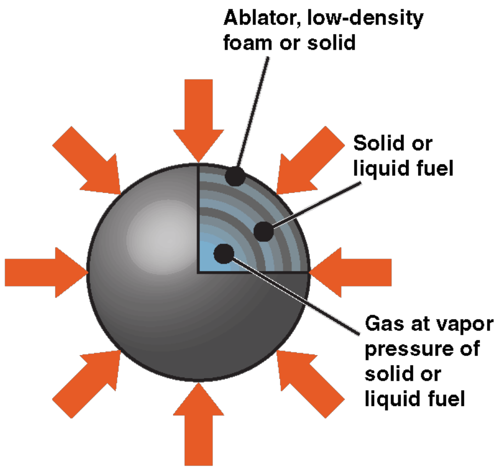
- **Solid State lasers: electrically pumped by efficient laser diodes**
  - **Advantages**
    - Vast majority of ICF/HEDP facilities are solid state (flashlamp pumped)
      - Diode pumped, high rep rate (>~10 Hz) being deployed for PW systems
    - Numerous applications in industry, science, and national security
      - Applications will drive diode costs down , increase e-0 efficiency and expand supply chain
    - Flexible high power performance
      - Temporal formats from fsec (10^{-15}seconds) to CW
    - Flexible Wavelength (non-linear frequency conversion) with good efficiency
      - Electrical –Optical efficiency (research to improve is a major goal!)
        - 1 micron (~25%)
        - 0.5 micron (>18%) dependent on temporal pulse format
        - 0.35 micron (~18%) dependent on temporal pulse format
    - Bandwidth > 10THz for LPI and imprint mitigation (impact on laser e-o efficiency)
      - Wavelength flexibility can also be advantageous for imprint mitigation
      - Large bandwidth (>10 THz) possible with beam strategy and multiple materials
      - Temporal and spatial approaches to mitigate LPI (non-linear optics (OPA exploitation,STUD pulses)
    - Architecture flexibility possible
      - Most optical components will see fundamental wavelength with increased damage threshold
  - **Challenges**
    - LPI will be issue without bandwidth or STUD pulses
    - ($/Joule) Gain media requires high precision fabrication, diode costs (($/watt) are high)
      - More research required for pulsed laser applications
      - Diode ”robustness” impact on operability
    - High non-linear index (n_2) impacts architecture and possibility “temporal coherence” strategies
    - Zooming will require novel architectures or innovation

Solid-state lasers used in present implosion facilities employ technologies and approaches developed in the 1990's

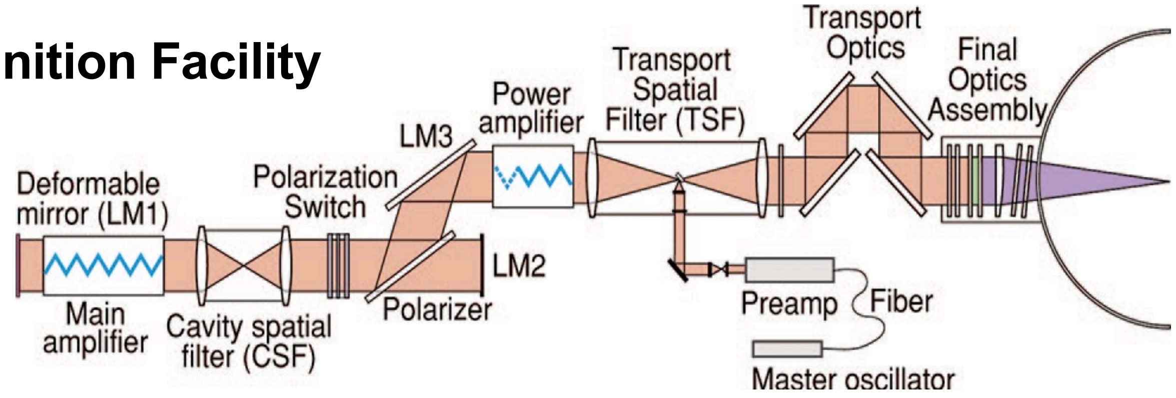
Laser Indirect Drive (LID)



Laser Direct Drive (LDD)



National Ignition Facility



National Ignition Facility *

- ~ 2 MJ (UV)
  - "unit cell" ~10 kJ UV (20 kJ 1 micron)
- 192 (~40×40 cm^2) beams grouped in 48 quads
- polar configuration
- ~ 1 shot per 8 hours
- Bandwidth ~<100 GHz

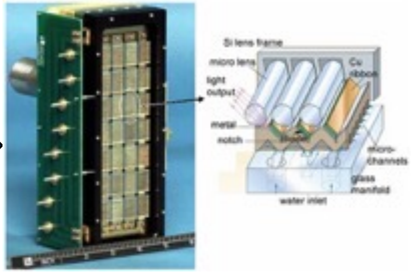
OMEGA-60 Laser †

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

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

Energy flow in a DPSSL direct-drive (LDD) target tomorrow ("NIF-like laser")

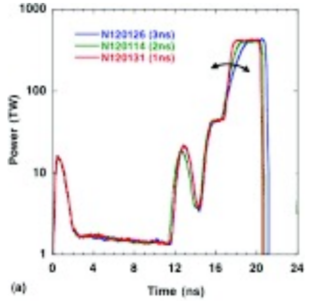
Electricity from the "grid" (10.3MJ)



Laser diodes (6.7 MJ)

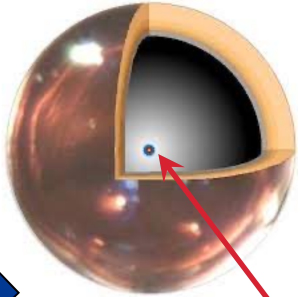
4 MJ at 1052-nm laser

Frequency conversion



~2 MJ at 350 nm (~18% E-O efficiency)

~1.8 MJ absorbed

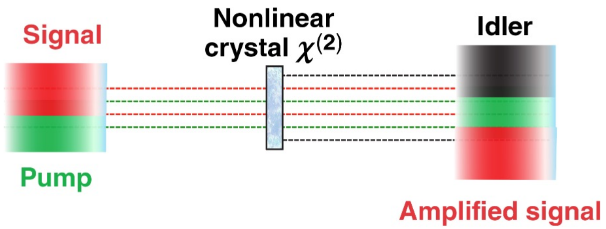


~0.1 MJ imploded target

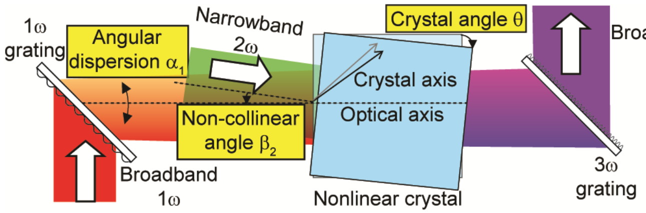
>100 MJ of fusion

IFE requires 21st century Lasers:LLE is developing FLUX a broad band (~10-15 Thz), UV (350 nm) laser employing novel non-linear optical schemes to explore LPI with an "incoherent" source

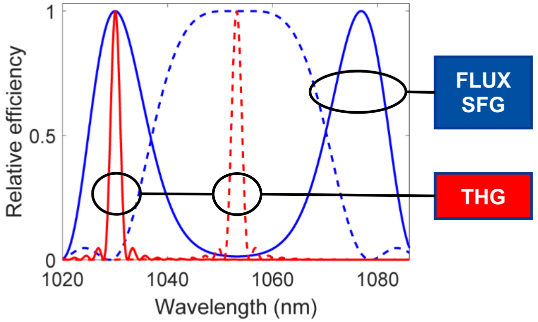
Collinear Optical Parametric Amplifier (COPA) near degeneracy



Sum Frequency Generation (SFG) boosts broadband IR signal and idler beams to UV

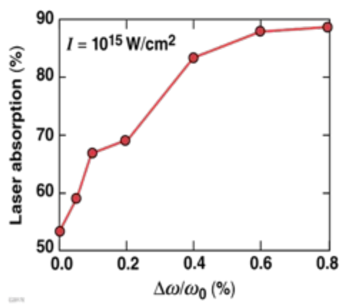


Simulated SFG + THG outputs

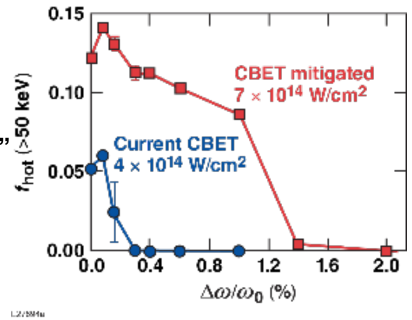


- **Fourth Generation solid-state laser (FLUX) : Broadband ($\Delta\omega/\omega_0$ ~ 1.5%) 350nm "to expand LPI-free parameter space" for all laser ICF/HEDP approaches and imprint (laser direct drive)**

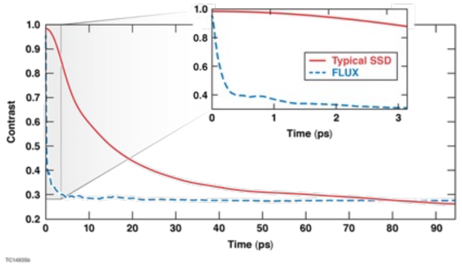
Absorption



"Hot Electrons"



Laser Imprint

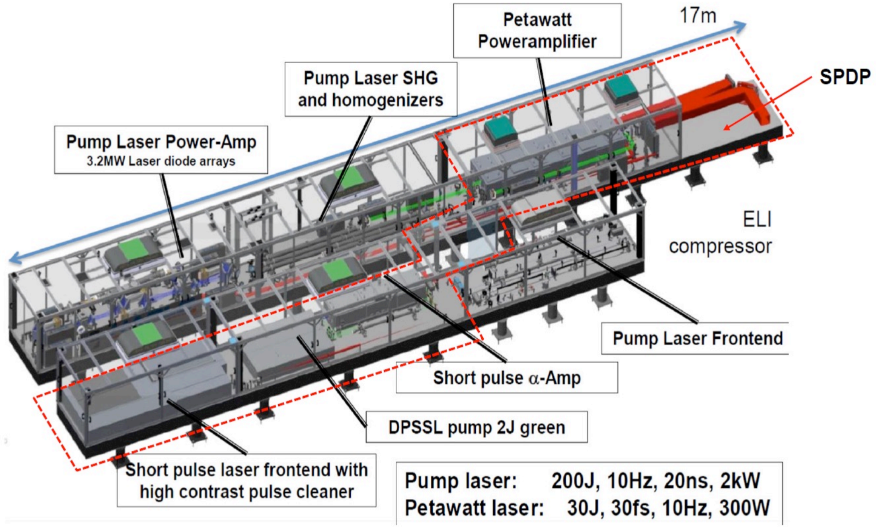


Flux will be complete in the fall of 2023 and transported to the OMEGA chamber (60 beam 30 kJ) where experiments will begin in late 2024 to address Imprint and LPI

The state-of-the-art for diode-pumped, solid-state lasers (DPSSLs) has advanced significantly driven by commercial and scientific applications and national security (Directed Energy Weapons)

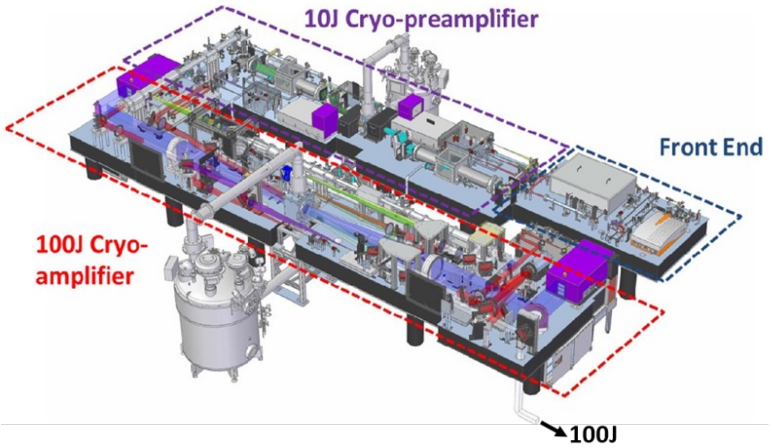
UR LLE

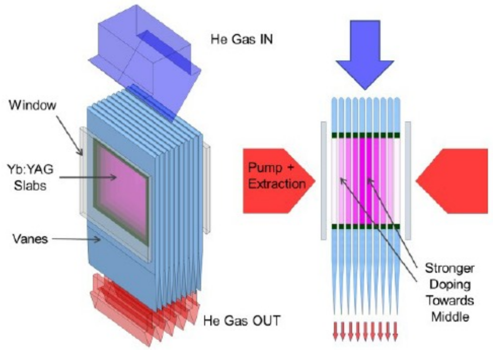
HAPLS pump laser @ ELI Beamlines



- Nd:phosphate glass slabs
- RT helium gas cooling

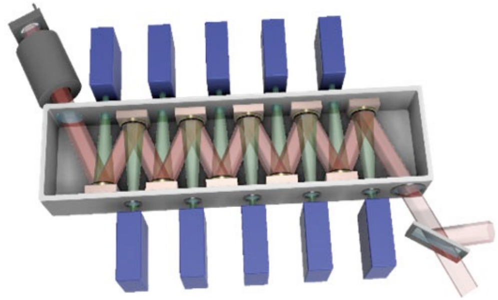
DiPOLE-100X at HIBEF/EuXFEL

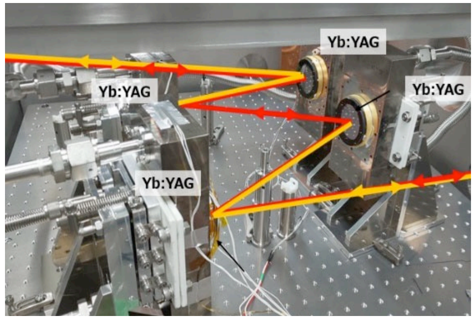




- Yb:YAG ceramic slabs
- cryo helium gas cooling

SENJU
Super-Energetic Joint Unit

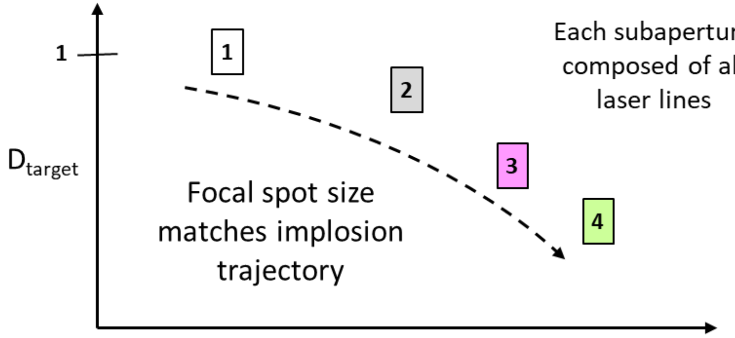


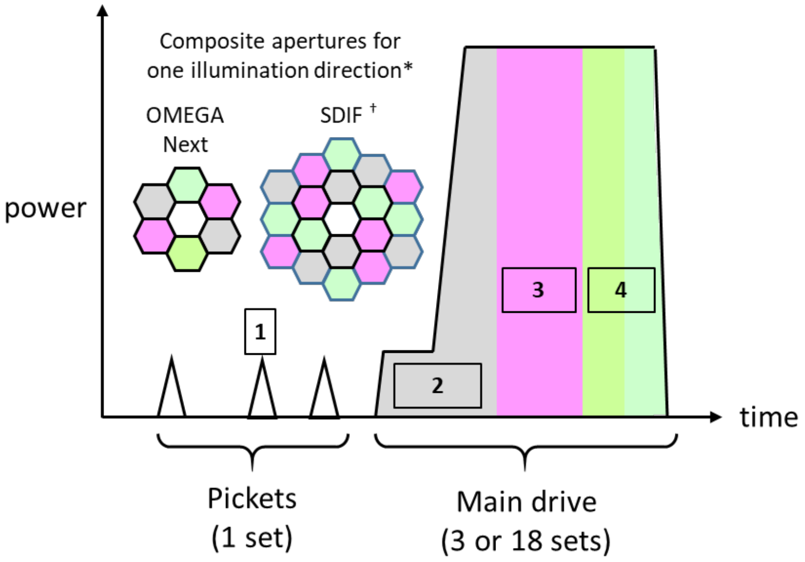


- Yb:YAG ceramic active mirrors
- cryo conduction cooling

Out of the Box Concepts:StarDriver* employs many (10^3 to 10^5) relatively small (cm-scale aperture) beamlines to deliver broadband irradiation to Laser Direct Drive (LDD) targets

- **Lasers operating at many discrete wavelengths** spanning the spectrum required to mitigate or even suppress laser plasma instabilities (LPIs).
  - Ideally, lasers incoherently interfere only on target
- **Smaller apertures enable a wider range of gain material options and addresses "supply chain challenges"**
- **Off-the-shelf optical components** will spur competitive commercial development leading to economies of scale
- **Moderate scale (100s J)** could benefit industrial and other applications
- **Modular approach provides scalability** across a range of ICF and IFE facilities to enable complex pulse shapes and focal spot zooming to optimize LDD drive.
- **Employ proven DPSSL architectures and enable new concepts** to improve system performance, efficiency, and reliability.





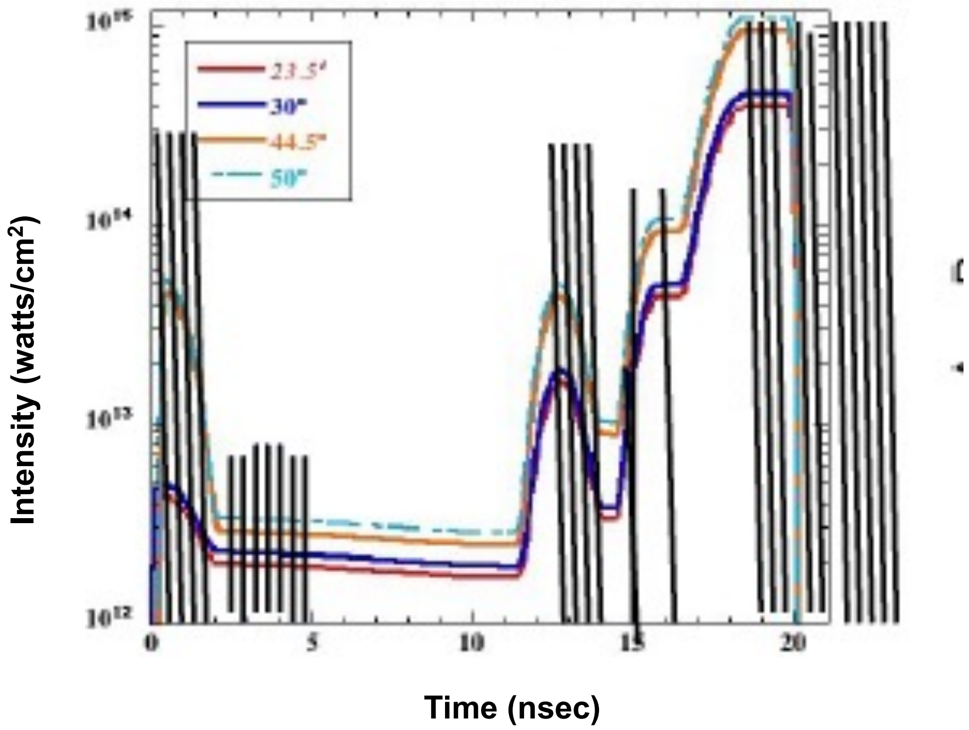
* D. Eimerl *et al.*, "StarDriver: A Flexible Laser Driver for Inertial Confinement Fusion and High Energy Density Physics," J. Fusion Energy vol. 33, pp. 476–488 (2014).

Out of the Box Concepts: STUD pulse approach[1]

Stud pulse concept

- Control LPI by modulating laser pulse in time at the Laser –plasma instability growth time
- Scramble speckles (hot spots) in space
- Laser is a series of short pulses rather than continuous in time
- Research underway at Colorado State University CSU) funded by ARPA-E

Representative NIF Ignition Pulse



[1] Bedros Afeyan

Polymath Research Inc.

Even Einstein would be impressed!

That stimulated emission idea has sure paid off!