Nd: Glass Laser Design for Laser ICF Fission Energy (LIFE)

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Fusion Energy Systems and Science

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NIF is the origin of LIFE

- Fluence is identical
- He cooling enables high average power
- Diode pumping enables high efficiency
LIFE laser system

- 17 MW
- 1.3 MJ
- 13.3 Hz

Availability (Optics durability or lifetime)

Targeting accuracy
- 2 μrad, Hot Spot Ignition
- 0.4 μrad, Fast Ignition

Efficiency & cost
- $\eta > 10\%$
- $\$ < \$100/W$

Thermal management
- 250 W/cm², 1ω output
NIF architecture is well suited for a LIFE Laser fusion driver

• Key features
  — Close to optimal and uniform aperture size
  — Number of beams effectively uses solid angle of target chamber
  — Operating fluence is sub-damage AND well saturated
  — Could be run at ~ Hz repetition rates with flowing-He cooling
Laser diodes and helium gas cooling enable a NIF-like architecture to meet LIFE driver requirements.

High Power Diode Arrays

100 kW peak power

High Speed Gas Cooling

3 W/cm² cooling (average)

These technologies have been developed as part of the Mercury HAPL Project.
Mercury Laser at LLNL
- 50 W/cm²
- Scalable architecture
- 0.3 M shots to date

• Up to 617 W achieved
• 0.3 Million shots to date in consecutive 0.5 - 2 hr operations
- LLNL/DOD Heat Capacity Laser
- 10 x 10 ceramic Nd:YAG
  — 10 sec. burst mode operation
  — > 250 W/cm²
Eight LIFE Engine options have varying laser energy, power, and pulselength requirements

<table>
<thead>
<tr>
<th>Fusion Power (MW)</th>
<th>Fusion Yield (MJ)</th>
<th>Ignition Type</th>
<th>( \lambda_{\text{comp}} ) (( \mu \text{m} ))</th>
<th>Illumination Geometry</th>
<th>( E_{\text{comp}} ) (MJ)</th>
<th>( P_{\text{comp}} ) (TW)</th>
<th>( \tau_{\text{esp}} ) (ns)</th>
<th>( 1\omega \tau_{\text{esp}} ) (ns)</th>
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</thead>
<tbody>
<tr>
<td>500</td>
<td>37.5</td>
<td>HSI</td>
<td>0.35</td>
<td>NIF-like</td>
<td>1.3</td>
<td>320</td>
<td>4.4</td>
<td>6.2</td>
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<td></td>
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<td>FI</td>
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<td></td>
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<td>LIA</td>
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<td>130</td>
<td>4.7</td>
<td>6.1</td>
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<tr>
<td>1000</td>
<td>75</td>
<td>HSI</td>
<td>0.35</td>
<td>NIF-like</td>
<td>1.9</td>
<td>423</td>
<td>4.5</td>
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<td>FI (150 kJ)</td>
<td>0.35</td>
<td>NIF-like</td>
<td>0.63</td>
<td>139</td>
<td>4.5</td>
<td>6.4</td>
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<td>0.53</td>
<td>NIF-like</td>
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<td>238</td>
<td>3.0</td>
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<td>LIA</td>
<td>0.89</td>
<td>300</td>
<td>3.0</td>
<td>3.9</td>
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</tbody>
</table>

Fast-Ignition Options use a 10 ps, 1.053 \( \mu \text{m} \) ignition laser

FI = fast ignition
HSI = hot-spot ignition
LIA = low-incidence angle

\( \tau_{\text{esp}} \) = equivalent square-pulse length
\( \lambda_{\text{comp}}, E_{\text{comp}}, \) and \( P_{\text{comp}} \) are compression laser wavelength, energy, and peak power
The current baseline design produces $3\omega$ pulses using a NIF-like multipass architecture

- Amplifier aperture is 20-cm x 40-cm
- Magnification factors are adjusted to give desired fluence at final optics
Optical finishing defects are seed locations for “high average power” crack growth

- With NIF finishing specifications slabs must be sliced into 4 or 5 slablets
- New glass compositions or finishing methods may enable a single slab
Thermal management of LIFE laser components is facilitated by flowing He gas cooling.
Amplifier Line Replaceable Unit (LRU) concept has been developed.
A NIF equivalent Tripler design (Type I/Type II) using DKDP will achieve high efficiency

DKDP (NIF DKDP shown below)

- Optimized for frequency tripling Haan pulse (58% efficiency)
- Thermally robust (95-99%D)
- $3\omega$ fluence 6 J/cm$^2$

40 x 40-cm aperture

Doubler

Tripler
Diodes are experiencing rapid learning

CW diode bar output increased 35x since 1988

- Mercury diodes, 2002
- $0.35$ Mercury price quote, 2007
- $0.09$ Vendor est., packaged edge emitters
- $0.007$ Vendor est., 20 GW VCSELs
- $0.025$ LLNL Eng’g est., 5 GW edge emitters
- $0.0072$ LLNL Eng’g est., 2.8 GW, VCSELs

Diode bar prices drop with growing market

- $100$ W bar 60% learning curve
- Potential of VCSELs
- LIFE

Cumulative number of bars vs. Cost ($/W$)

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Surface emitters have larger optical emission area and higher safety margin for operation

- Output irradiance reduced by 50x in VCSELs results in higher reliability
- Wafer-scale production process enables substantial cost reduction
- Vendor cost estimate based on cell phone technology is $0.007/W
At $0.01/Watt diodes are a small fraction of cost
Diode pumping allows NIF laser technology to meet LIFE efficiency requirements

<table>
<thead>
<tr>
<th>Efficiency (%)</th>
<th>NIF (3ω) Lamp-Pumped</th>
<th>NIF (3ω) &amp; Diodes Today</th>
<th>LIFE (3ω) &amp; Diodes</th>
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</thead>
<tbody>
<tr>
<td>Power Conditioning</td>
<td>82</td>
<td>88</td>
<td>90</td>
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<tr>
<td>Diodes / Lamps</td>
<td>50</td>
<td>60</td>
<td>80</td>
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<td>Pump transport</td>
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<td>98</td>
<td>99</td>
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<td>Absorption</td>
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<td>Quant Defect</td>
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<td>1 – Decay Fraction</td>
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<td>Extraction, Fill &amp; 1ω Transport</td>
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<td>37</td>
<td>60</td>
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<tr>
<td>Freq Conv &amp; 3ω Transport</td>
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<td>64</td>
<td>70</td>
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<tr>
<td>Cooling</td>
<td>100</td>
<td>100</td>
<td>90</td>
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<tr>
<td>Total Efficiency (%)</td>
<td>0.66</td>
<td>5.0</td>
<td>13.3</td>
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</tbody>
</table>
A hot, thin Fresnel lens (diffractive optic) is our choice for the LIFE focusing optic

25-m Focal Length Fresnel Lens

1 mm thick, 80 cm diameter

- Static loss due to neutrons saturates quickly and drops when heated
- Laser operations will replace optic as loss becomes excessive
We have made large Fresnel optics at LLNL
We have made high damage threshold large scale diffractive optics.
LIFE targeting requirement is similar to that of other demanding systems

Airborne Laser

~1 $\mu$rad angular precision
(~10 cm, 100 km)

LIFE

2 $\mu$rad precision (HS, 50 $\mu$m, f = 25 m)
0.4 $\mu$rad (FI, 10 $\mu$m, f = 25 m)
Preliminary cost model based on NIF experience

- Costs are based on NIF historical data with corrections for changes in technology and experience
  - Flashlamp pumping → diode pumping
  - Passive cooling → active cooling of slabs and diodes
  - Addition of a 3rd spatial filter for neutron shielding
  - Learning

- Scaling factors are applied to account for variations in beam size, wavelength ($1\omega$, $2\omega$, and $3\omega$), repetition rate, and system size

- We are developing a model that accounts for detailed beamline design parameters that have been omitted here
Laser cost is reasonable when pump-diode cost is \(\leq 1\text{¢/W}\)

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<th>Nth System Cost ($M)</th>
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<td>NIF-like</td>
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<td>FI (100 kJ)</td>
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<td>NIF-like</td>
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A LIFE pilot plant could be operational by 2020 and a commercial demo by 2025

<table>
<thead>
<tr>
<th>Research and Dev Plan</th>
<th>Ignition on NIF</th>
<th>Fast Ignition Dev on NIF</th>
<th>Laser Components</th>
<th>LIFE Laser Beamlet</th>
<th>Diode production</th>
<th>Pilot Optic Production</th>
<th>Pilot Plant</th>
<th>Demo Plant Construct</th>
<th>Demo Plant Operations</th>
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<tr>
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<td>Design</td>
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<td>Downselect &amp; Facilitize</td>
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<td>Reliability</td>
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Fiscal Year (20xx)

| 08 | 09 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 |

- A LIFE pilot plant could be operational by 2020
- A commercial demo by 2025
Conclusions

• NIF architecture with diode laser pumping and He-gas cooling is our baseline LIFE Laser design

• Optimization of the architecture will further improve system performance and economics

• Emerging but less proven technologies could also improve performance and economics

• We are developing a full sub-system R&D path outline

NIF is a prototype for LIFE laser performance
Acknowledgement of contributors

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