DPSSL Systems:
The Next Generation

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Presented by
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A solid-state laser for IFE must exhibit certain properties

• Technical laser requirements
  – Energy/power to drive target
  – Beam conditioning
  – Efficiency $\Rightarrow$ optical-optical efficiency $> 0.2$
  – ASE $\Rightarrow \alpha \cdot \ell < 4.5$
  – Beam filamentation $\Rightarrow \delta B < 1.8$

• IFE - specific constraints
  – Cost
  – Rep rate
  – RAM

Challenge – What is the gain medium?
How did we come to use Yb:S-FAP for a DPSSL?

- In the early 1990’s, the primary concern was minimizing the number of costly diode arrays
- New Yb$^{3+}$-doped materials were selected for long (1 msec) storage lifetimes and other desirable properties
Mercury (and other) laser systems have rapidly advanced laser - diode technology

- Monolithic package has driven down cost
- Mercury diode bar cost - $1.30/W_{peak}

- Diode cost will continue to drop
  - Advanced manufacturing technologies
  - Performance improvements
  - Expanding market: DoD, laser machining,…

- 80 kW_{peak} Mercury arrays can scale to 10’s of MW
Diode - bar prices are dropping with growing market volume

- Cost data follows a classic “learning curve”
- Every doubling of quantity cuts the cost 41%

Laser diodes will eventually become affordable for IFE
Challenge – What should be the next-generation gain medium?

- Yb$^{3+}$:S-FAP — special crystal, carefully chosen

- Nd$^{3+}$:Glass — tailored phosphate glass, produced in large volumes at low cost

- Optical (transparent) ceramics — hybrid, combines technical and chemical-engineering advantages

Down-selection is a multi-dimensional problem involving numerous cost, performance, and engineering issues
Yb$^{3+}$:S-FAP — an apatite-structure crystal demonstrated on the Mercury system

- **Strength**
  - Yb$^{3+}$ ion has a long storage lifetime (~1 msec,) minimizing diode-array count

- **Weaknesses**
  - Development is being driven by only one program – Mercury
  - Limited aperture sizes (Mercury is 3 cm x 5 cm), but may be enlarged by crystal bonding (stitching)
  - Quasi-three level laser (at room temperature)
Nd³⁺:Glass — used in many generations of fusion lasers

**Strengths**
- Large apertures (NIF slabs are 40 cm x 70 cm)
- Production capability is well established
- Four-level laser (at RT)

**Weaknesses**
- Nd³⁺ lifetime only 0.36 msec (3x more diodes than Yb³⁺)
- Low thermal conductivity (~0.0058 W/cm·°C, about 4x less than Yb:S-FAP)
Optical ceramics have arrived!

10 x 10 x 2 cm Nd:YAG ceramic slabs

- Ceramic media sizes scale like glass
- Optical quality is comparable to that of NIF glass

100°K Yb3+:YAG ceramic is a potential large-aperture medium for a four-level IFE DPSSL driver

Today’s slabs are generally smaller than those needed for IFE

- Today
  - 3 x 5 cm²
  - 10 x 10 cm²
  - 13 x 20 cm²
  - Nd:Glass 40 x 70 cm²

- IFE
  - 17x Yb:S-FAP
  - 28x Yb:YAG ceramic
  - 40 x 70 cm²

Only Nd:Glass is at the required IFE slab size
We are embarking on a cost analysis of candidate DPSSL systems for IFE

Comparison of Yb:S-FAP, Nd:Glass, and Yb:YAG (ceramic) - based IFE drive lasers:

- Nd:Glass - based system
  - Traceable to NIF beam line
  - Leverages technology base developed for NIF: large optic finishing, beam-line bundling, switchyard, and LRUs

- Yb:S-FAP - based system
  - Traceable to Mercury architecture, but using a NIF-like configuration
  - Leverages design of Mercury amplifiers

- Yb - doped optical ceramics
  - Scale like glass but has long storage time
  - Replace NIF glass slabs with Yb:YAG ceramic
  - Require large-scale cryo-cooling
Comparison (size and number) of beam lines suggests that cryogenic Yb:YAG has the smallest “footprint”

Nd:Glass
- 40 cm x 40 cm aperture
- 4 beam lines per port
- 192 total beam lines

Yb:S-FAP
- 13 cm x 20 cm aperture
- 32 beam lines per port
- 1536 total beam lines

Yb:YAG ceramic
- 40 cm x 40 cm aperture
- 8 beam lines per port
- 384 total beam lines
Diode - pumped Nd:Glass head with He cooling

- Multiple - thin - slab architecture is required for thermal management
  - Center slabs are 1.43 cm thick
  - Outer slabs are 0.72 cm thick
- Heat intensity at all interior - slab surfaces is 0.92 W/cm²
Facility comparison

Yb:S-FAP facility
1536 beam lines

Nd:Glass facility
192 beam lines
“End – on” comparison of aperture areas (for half of the beam lines)

- Nd:Glass
- Yb:YAG ceramic
- S-FAP
Comparison of rare-earth absorption features: linewdths set tolerances on pump-diode wavelengths

Spectrally-resolved absorption cross sections (normalized)

<table>
<thead>
<tr>
<th>Material</th>
<th>Linewidth (FWHM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yb:YAG 100 K</td>
<td>15 nm</td>
</tr>
<tr>
<td>Yb:YAG RT</td>
<td></td>
</tr>
<tr>
<td>Nd:Glass</td>
<td>12.5 nm</td>
</tr>
<tr>
<td>Yb:S-FAP</td>
<td>3.4 nm</td>
</tr>
</tbody>
</table>

Lower-cost diodes
Changes involved in converting a NIF beam line to 10 Hz operation

<table>
<thead>
<tr>
<th>NIF technology</th>
<th>Beam line upgrade (10 Hz operation)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flashlamps</td>
<td>Diode arrays</td>
</tr>
<tr>
<td>4.3 cm thick Nd:Glass slabs</td>
<td>• Thinner Nd:Glass slabs</td>
</tr>
<tr>
<td></td>
<td>• Yb:YAG ceramic slabs</td>
</tr>
<tr>
<td></td>
<td>• Mercury-like Yb:S-FAP amplifier heads</td>
</tr>
<tr>
<td>KDP PEPC</td>
<td>KD*P PEPC</td>
</tr>
<tr>
<td>Air slab cooling</td>
<td>He cooling</td>
</tr>
<tr>
<td>KDP harmonic generation</td>
<td>KD*P harmonic generation</td>
</tr>
</tbody>
</table>
Salient features of three candidate solid-state laser systems for IFE

Baselined systems are each 4 MJ$_{1\omega}$ with $\geq$ 20% optical-optical efficiency

<table>
<thead>
<tr>
<th></th>
<th>Yb:S-FAP</th>
<th>Nd:Glass</th>
<th>Yb:YAG (100$^\circ$K)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gain medium</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Laser type</strong></td>
<td>Quasi-three level</td>
<td>Four level</td>
<td>Four level</td>
</tr>
<tr>
<td><strong>Storage time</strong></td>
<td>1 ms</td>
<td>0.36 ms</td>
<td>1 ms</td>
</tr>
<tr>
<td><strong>Peak diode pump power</strong></td>
<td>20 GW</td>
<td>56 GW</td>
<td>20 GW</td>
</tr>
<tr>
<td><strong>Absorption FWHM</strong></td>
<td>3.4 nm</td>
<td>12.5 nm</td>
<td>15 nm</td>
</tr>
<tr>
<td><strong>Operating temperature</strong></td>
<td>Room Temperature</td>
<td>Room Temperature</td>
<td>100 K</td>
</tr>
<tr>
<td><strong>Aperture size</strong></td>
<td>13 cm x 20 cm (near - normal incidence)</td>
<td>40 cm x 40 cm (Brewster)</td>
<td>40 cm x 40 cm (Brewster)</td>
</tr>
<tr>
<td><strong>Number of beam lines</strong></td>
<td>1536</td>
<td>192</td>
<td>384</td>
</tr>
<tr>
<td><strong>Total number of slabs</strong></td>
<td>21,504</td>
<td>10,368</td>
<td>1,536 – 23,040</td>
</tr>
<tr>
<td><strong>Total aperture area</strong></td>
<td>40 m$^2$</td>
<td>31 m$^2$</td>
<td>61 m$^2$</td>
</tr>
</tbody>
</table>
# Heat-removal tradeoffs of the three systems

Waste heat is assumed dumped at room temperature

<table>
<thead>
<tr>
<th>Gain medium</th>
<th>Yb:S-FAP</th>
<th>Nd:Glass</th>
<th>Yb:YAG (100 K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{\text{thermal from diodes and operating temperature}}$</td>
<td>133 MW 268 K</td>
<td>133 MW 268 K</td>
<td>133 MW 268 K</td>
</tr>
<tr>
<td>$\frac{P_{\text{req for cooling}}}{P_{\text{thermal}}} = 2.5 \left( \frac{T_a - T_c}{T_c} \right)^{4/3}$</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
</tr>
<tr>
<td>Quantum defect</td>
<td>0.13</td>
<td>0.23</td>
<td>0.09</td>
</tr>
<tr>
<td>$P_{\text{thermal from laser slabs and operating temperature}}$</td>
<td>23 MW 268 K</td>
<td>42 MW 268 K</td>
<td>16 MW 100 K</td>
</tr>
<tr>
<td>$\frac{P_{\text{req for cooling}}}{P_{\text{thermal}}} = 2.5 \left( \frac{T_a - T_c}{T_c} \right)^{4/3}$</td>
<td>0.11</td>
<td>0.11</td>
<td>6</td>
</tr>
<tr>
<td>Power required for thermal management</td>
<td>17.2 MW</td>
<td>19.3 MW</td>
<td>111 MW</td>
</tr>
<tr>
<td>Gain medium</td>
<td>Yb:S-FAP</td>
<td>Nd:Glass</td>
<td>Yb:YAG ceramic</td>
</tr>
<tr>
<td>-------------------</td>
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<td>----------</td>
<td>----------------</td>
</tr>
<tr>
<td>Diodes</td>
<td>😊</td>
<td>😞</td>
<td>😊</td>
</tr>
<tr>
<td>Gain Media</td>
<td>😞 😐 😞</td>
<td>😊 😊 😐</td>
<td>😊 😊 😐</td>
</tr>
<tr>
<td>Cooling</td>
<td>😊</td>
<td>😊</td>
<td>😞</td>
</tr>
</tbody>
</table>

We’re still deciding!
Together, NIF and Mercury technologies enable demonstration of a DPSSL - based IFE beam line.