High efficiency, diode pumped Petawatt lasers for the next generation particle accelerators and secondary sources

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The laser: 50 years of discoveries
Testimony by Charles Townes

“The history of the laser is a perfect example of the impact of basic research, not only on science, but also on economy – a spectacular impact, often completely unexpected.”
1996: The First Petawatt Laser, invented at LLNL: 600 J, >1 PW

Petawatt achievements and discoveries:

- 1.3-PW = 1,300,000,000,000,000 Watts
- \( \sim 10^{21} \) W/cm\(^2\)
- 10-100-MeV electron beams
- Laser made proton beams
- Hard x-rays and gamma-rays
- Photo-fission
20 years later:
HAPLS laser runs 200,000 times faster than the original 1996 Petawatt
Worldwide scientific laser facilities mostly meet the demands for proof of principle experiments.

List of lasers indicative and not complete:
- Ti:Sapphire (Ti:Sa)
- Nd:glass (Nd:glass)
- Yb:glass (Yb:glass)
- OPA (Optical Parametric Amplifier)

- Ultrafast
- High-field
- Mat. Phys.
- ICF/IFE/HED
- WDM SPL Pumps
- Industrial Appl.

- Average Power
- Operational
- Conceptual
- In Build
Commercial and advanced scientific short pulse laser applications require high repetition rate.
Heat can be extracted through the “edge” or the “face”

**Rod amplifiers**
- Conductive cooling through edges
- Stress orthogonal to laser beam
- High energy storage

**THIN DISK: “active mirror”**
- Conductive cooling through back side
- Stress parallel to laser beam
- Low energy storage

**multislab-face-cooling**
- Conductive/convective cooling with liquid (National Energetics) or Helium gas (LLNL, RAL)
- Stress parallel to laser beam
- High energy storage
LLNL pioneered gas-cooling of high energy laser amplifiers in the eighties: slabs are cooled by rapidly flowing He-gas

- Face cooled Nd:Glass slabs
- Room temperature Helium gas coolant
- Gas acceleration vanes Mach 0.1
- Cooled ASE Edge claddings
Two architectures for high energy DPSSL recently demonstrated: the LLNL’s “HAPLS”, and Rutherford’s “DiPOLE100”

Delivers 200J, 20ns, 10Hz and 30J, 1PW, 30fs, 10 Hz

Delivers 100J, 10ns, 10Hz
Diode pumping has a significant impact on system efficiencies

<table>
<thead>
<tr>
<th>Waste energy per 1J laser output</th>
</tr>
</thead>
<tbody>
<tr>
<td>250J</td>
</tr>
<tr>
<td>200J</td>
</tr>
<tr>
<td>150J</td>
</tr>
<tr>
<td>100J</td>
</tr>
<tr>
<td>50J</td>
</tr>
<tr>
<td>0J</td>
</tr>
</tbody>
</table>

**Ti:Sa PW Efficiency**

<table>
<thead>
<tr>
<th>WP</th>
<th>0.4%</th>
<th>2.6%</th>
</tr>
</thead>
<tbody>
<tr>
<td>EO</td>
<td>0.6%</td>
<td>3.8%</td>
</tr>
</tbody>
</table>

- Output
- Slab Heating
- Fluorescence
- Transport
- Unconverted Light
- Pump light loss
- Pump Heat
- Electronics Heat
- Refrigeration
Scale a flashlamp-pumped Ti:Sa laser to TeV-Collider size and you need a nuclear power plant in your backyard.
HAPLS is designed to deliver Petawatt peak power laser pulses at energy 30J and 10Hz repetition rate = 300 Watt

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy 0.8 µm</td>
<td>≥30 J</td>
</tr>
<tr>
<td>Pulse length</td>
<td>≤30 fs</td>
</tr>
<tr>
<td>Peak power</td>
<td>≥1 PW</td>
</tr>
<tr>
<td>Pre-pulse power contrast</td>
<td>≤10^{-9} ≤ c ≤10^{-11}</td>
</tr>
<tr>
<td>Energy stability</td>
<td>0.6% rms</td>
</tr>
<tr>
<td>Technology</td>
<td>DPSSL pumped Ti:sapphire CPA</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>10 Hz</td>
</tr>
<tr>
<td>Electrical consumption</td>
<td>&lt;150 kW</td>
</tr>
</tbody>
</table>
LASER ON
High Power Operations
Eyewear Required
HAPLS today....at ELI Beamlines ready for installation
Today, the HAPLS delivers 16J of broadband laser pulses at 3.3 Hz; full aperture is pulse duration 28fs.

\[ \mu = 28.1 \text{ fs} \]
\[ \sigma = 1.4 \text{fs} = 5.0\% \]
HAPLS relies on a diode pumped, indirect chirped pulse amplification architecture ("diode pumped laser pumped laser")
• The HAPLS Pump laser delivers 1.2 MJ/hour today
• The HAPLS Petawatt laser system delivers 190 kJ/hour

Ramped to its full performance at ELI, HAPLS will deliver 1MJ/hr of Petawatt, 30fs pulses
The average power scalability of energetic Ti:Sapphire (and OPCPA) laser is constrained by the availability of pump lasers.

The short gain lifetime and the large quantum defect make Ti:Sapphire drives the cost of the pump laser and makes it an unattractive HAP laser medium.
The HAPLS pump architecture utilizes dual diode-pumped surface-cooled multislab amplifiers in a 4-pass polarization switched architecture.

![Diagram of HAPLS pump architecture](image)

- **Adaptive optic**
- **He gas cooling**
- **Diodes**
- **Spatial Filter**
- **Relay**
- **Polarizer**
- **HAP Compressor**
- **Ti:sapphire Amplifier**
- **Frequency Converter**
- **Long Pulse Front End**
- **Amp 1**
- **Amp 2**
The dual diode-pumped surface-cooled multislab amplifier in a 4-pass polarization switched architecture is a template for high average power high peak-power systems.
The HAPLS pump laser could be converted to a 150J, 150fs, 10Hz secondary source driver: SHARC

Continuous 1hr run delivering 100Joule pulses at 340W

Energy stability scales with output energy. Predicted <0.35% @ 200J

Output beam profile
Based on HAPLS pump laser and NIF ARC technology, LLNL has developed a concept for a **Scalable High-average-power Advance Radiographic Capability (SHARC)**

- SHARC is a low-risk high-TRL extension of HAPLS pump laser technology
- 150J, 150fs, 10Hz, 90/110 dB temporal contrast
- 10-Hz PW (150J/150fs) at greater efficiency than HAPLS (~5% Wall plug efficiency)
- HAPLS diode-pumped Nd:Glass pump laser with broadband mixed-glass frontend and LLE’s Short Pulse OPA seed technology
- High efficiency, actively cooled MLD-grating laser pulse compressor
- Application space targets proton-/neutron-particle beam and high brightness x-ray generation
Based on HAPLS pump laser and NIF ARC technology, LLNL has developed a concept for a Scalable High-average-power Advance Radiographic Capability (SHARC)
HAPLS-100 and SHARC could get us to kW to ~10kW of average power (at Petawatt peak power).

But we need 100s of kW for TeV Collider stage.
High-Power Single-Aperture Laser Beamline Performances

Pushing the frontiers of high-power applications and high-intensity science requires next-generation high repetition-rate high-energy solid state lasers.
If we normalize this plot by the beam area in the final amplifier, the axes become proportional to laser media parameters: photon energy, gain cross-section, gain lifetime, gain bandwidth (i.e., transform limited pulse duration).

\[
\frac{h\nu}{\sigma} \cdot \Delta \nu
\]

\[
\frac{h\nu}{\sigma} \cdot \frac{1}{\tau_{\text{gain}}}
\]
Power Scaling for Energy-Storage Laser Media (simple scaling w/o architecture considerations)

\[ \frac{h \nu}{\sigma} \cdot \Delta \nu \]

![Graph showing laser media comparison](image)

**Table 1. Theoretical peak power.**

<table>
<thead>
<tr>
<th>Laser type</th>
<th>Cross section (10^-16 cm²)</th>
<th>Δν (THz)</th>
<th>τ (ns)</th>
<th>P_g (MW/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nd:glass phosphate</td>
<td>0.4</td>
<td>60</td>
<td>60</td>
<td>100</td>
</tr>
<tr>
<td>Nd:glass violet</td>
<td>1.4</td>
<td>60</td>
<td>60</td>
<td>100</td>
</tr>
<tr>
<td>Nd:glass combination</td>
<td>1.5</td>
<td>60</td>
<td>60</td>
<td>100</td>
</tr>
<tr>
<td>Yb:glass</td>
<td>2</td>
<td>120</td>
<td>60</td>
<td>100</td>
</tr>
<tr>
<td>Tm:glass</td>
<td>30</td>
<td>100</td>
<td>10</td>
<td>2000</td>
</tr>
<tr>
<td>Cr:LiF</td>
<td>1</td>
<td>50</td>
<td>11</td>
<td>1000</td>
</tr>
</tbody>
</table>

Stored energy can be extracted from laser medium with a high fluence single pulse, or multiple low-fluence pulses within the radiative lifetime.

Multi-pulse extraction reduces the effective fluence in the laser system and therefore moves the operating point into a manageable regime for low cross-section materials.
Efficient Diode-Pumped Media for High-Power Lasers (Single-pulse and Multi-Pulse Extraction)

\( \frac{h \nu}{\sigma} \)

Gain Bandwidth

Multi-Pulse Extraction

Single-Pulse Extraction

Laser Media
- Ti:Sa
- Nd:Y
- Yb:X
- Er:X
- Cr:X
- Tm:X

Optical Damage & B-Integral Limit

Efficient Diode Pumping

\( \frac{h \nu}{\sigma} \cdot \frac{1}{\tau_{gain}} \)
Power Scaling for Energy-Storage Laser Media: Damage Limited Fluence and Multi-Pulse Extraction

\[
\text{Min}\left[\frac{h\nu}{\sigma}, F_{\text{dam}}\right] \cdot \Delta \nu
\]

Laser Media:
- Ti:Sa
- Nd:G
- Yb:X
- Er:X
- Cr:X
- Tm:X

Gain Bandwidth

Duty cycle

\[\frac{h\nu}{\sigma} \cdot \frac{1}{\tau_{\text{gain}}}\]
Quantum Defect and Gain Lifetime for Energy-Storage Laser Media

\[ (1 - \eta_{QD}) \cdot \eta_{\text{conversion}} \cdot \eta_{\text{diode}} \]

Media down select for efficient CW Diode Pumping

Tm:YLF

Gain Bandwidth
High-Power Single-Aperture Laser Beamline Performances

Laser Media
- Ti:Sa
- Nd:G
- Yb:X
- Er:X
- Cr:X
- OPA
- Tm:X
- Gas

Pulse Energy

Operational
In Build
Conceptual
De-activated

Peek Power
- 1 PW
- 1 TW
- 1 GW
- 1 mW

Average Power
- 1 W
- 1 kW
- 1 MW

State of the Art Lasers
High-Power Applications
High-Field Laser Physics Factory
High-Field Discovery Science

Intensity [W/cm²] for 1 µm spot
- 10⁻¹⁰
- 10⁻¹¹
- 10⁻¹²
- 10⁻¹³
BAT: Big Aperture Thulium Laser. BAT is a high rep-rate PW-class architecture which scales to 300-kW average power

- Extension of HAPLS diode-pumped gas-cooled architecture
- Tm:YLF laser media (1.9um)
  - Commercially available in sizes for 300-kW
  - superior thermal wave front (-dn/dT vs thermal expansion)
  - anisotropic media - de-polarization not an issue
  - Pulse duration $40\text{fs} < t < 100\text{fs}$ TL
  - Two-for-one pumping by self-quenching in Tm enables low QD pump scheme

- True CW pumped:
  - Tm has long lifetime which when combined with the desired pulse repetition rates enables multi-pulse extraction and continuous pumping
  - Quasi-4-level losses are distributed among hundreds of pulses minimizing this effect
  - Efficient extraction at low fluence per pulse, low B, higher efficiency
  - $\sim40\times$ lower diode cost compared to HAPLS; lower electronics cost due to simplicity over QCW
  - Efficient high-power pump diodes consistent with Tm pumping already on the market

We have purchased 300kW-equivalent size Tm:YLF boules, produced our first amplifier slabs and characterizing the material further for its suitability
Block diagram of BAT

Oscillator → Pulse shaping and contrast enhancement → Stretcher → InnoLab

Integrated Controls

~750kW cw-laser diode arrays

300 kW Compressor

• Beam transport
• Target

Diode Arrays

3J @ 10kHz miniBAT amplifier

38J @ 10kHz BAT amplifier

Front End 3kW (300mJ @ 10kHz)
BAT emits 300kW from a single aperture

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gain medium</td>
<td>Tm:YLF</td>
</tr>
<tr>
<td>Architecture</td>
<td>Multi-pass, multi-pulse gas cooled</td>
</tr>
<tr>
<td>Output energy</td>
<td>30 J</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>10,000 Hz</td>
</tr>
<tr>
<td>Average output power</td>
<td>300 kW</td>
</tr>
<tr>
<td>Wavelength</td>
<td>~ 1.9 µm</td>
</tr>
<tr>
<td>Output fluence</td>
<td>0.7 J/cm²</td>
</tr>
<tr>
<td>B integral (Poweramp)</td>
<td>&lt; 0.1 radians (!!!)</td>
</tr>
</tbody>
</table>
BAT laser diodes are always on!!!

Commercial pump cw-diode arrays are available (150W/bar) from multiple vendors

808 nm pump band matches Nd:YAG pump wavelengths

<table>
<thead>
<tr>
<th></th>
<th>HAPLS</th>
<th>BAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser Average Power (kW)</td>
<td>0.3</td>
<td>300</td>
</tr>
<tr>
<td># of arrays</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Array Peak Power (kW)</td>
<td>800</td>
<td>188</td>
</tr>
<tr>
<td>Array Average Power (kW)</td>
<td>2.4</td>
<td>188</td>
</tr>
<tr>
<td>Emitting area (W x H cm²)</td>
<td>5.6 x 13.4</td>
<td>6.6 x 28.4</td>
</tr>
<tr>
<td>Duty Cycle (%)</td>
<td>0.3</td>
<td>100</td>
</tr>
<tr>
<td>Relative Cost / array</td>
<td>1</td>
<td>1.9</td>
</tr>
</tbody>
</table>

Diodes for a 300 kW class BAT system are only 1.9X the cost of the HAPLS arrays
Pushing the frontiers of high-power applications and high-intensity science requires next-generation high repetition-rate high-energy solid state lasers.
High-Power Single-Aperture Laser Beamline Performances

Pushing the frontiers of high-power applications and high-intensity science requires next-generation high repetition-rate high-energy solid state lasers.
Summary

- LLNL is exploring avenues to break the kW barrier for high peak power lasers to drive high flux x-ray, γ-ray, and particle beams.

- Performed extensive architecture and material study. Crucially important for high average power lasers is high wall-plug efficiency: reduce heat (once heat is in it’s expensive and hard to pull it out) and heat effects (heating-cooling gradients cause beam deterioration, break stuff and limit average power)
  - Direct CPA increases dramatically the efficiency; beam quality and temporal pulse contrast require additional attention
  - Long radiative lifetime gain media become available through multi-pulse extraction at safe energy extraction fluencies
  - CW-pumping reduces massively the capital cost for high average power DPSSL

Diode pumping has a significant impact on system efficiencies, but direct CPA lasers with multi-pulse extraction and cw- pumping will have even greater impact on efficiency and system feasibility for laser-plasma accelerator applications.
The repetition rate has a significant effect on the extraction and system efficiencies, depending on laser media.

Example: Yb-fiber Direct CPA

<table>
<thead>
<tr>
<th>PRF [kHz]</th>
<th>Single-Pulse Extraction</th>
<th>Multi-Pulse Extraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1000</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Efficiency

- **Direct CPA: High-PRF**
  - WP: 26%
  - EO: 34%

- **Direct CPA: Low-PRF**
  - WP: 2.0%
  - EO: 2.9%

The graph shows the relationship between PRF and extraction efficiency, with a clear distinction between single-pulse and multi-pulse extractions. The energy [J per J of short-pulse output] is also indicated, with different colors representing different energy levels and losses.
Use a long energy storage gain medium, CW-pumping, multi-pulse extraction and direct CPA and you can go GREEN.

LLNL 3.3 MW solar farm can power ~2x BAT.
Summary

• We have developed a conceptual design for a single-aperture, 300 kW Thulium:YLF Petawatt-class laser “BAT” consistent with requirements for laser wakefield accelerators

• The underlying technology is a modest extension of established LLNL gas-cooling and rep rated Petawatt technologies

• BAT makes use of a highly simplified laser architecture, multi-pulse extraction of CW-diode pumped Tm:YLF and thus providing good wall-plug-efficiency

• We have developed a list of system TRLs and challenges that will inform the strategic plan for R&D and RTP efforts

<table>
<thead>
<tr>
<th>System</th>
<th>Type</th>
<th>TRL Estimate</th>
<th>Integration Challenge</th>
<th>delivery horizon</th>
<th>E (J)</th>
<th>t (fs)</th>
<th>P_{av} (kW)</th>
<th>P_{peak} (PW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HAPLS</td>
<td>DPSSL+TiS</td>
<td>7</td>
<td>Low</td>
<td>today</td>
<td>30</td>
<td>&lt;30</td>
<td>0.3</td>
<td>1</td>
</tr>
<tr>
<td>SHARC</td>
<td>DP CPA Nd:Glass</td>
<td>6</td>
<td>Low</td>
<td>3yrs</td>
<td>150</td>
<td>150</td>
<td>1.5</td>
<td>1</td>
</tr>
<tr>
<td>Mini-BAT</td>
<td>DP CPA Tm:YLF</td>
<td>3-4</td>
<td>Medium</td>
<td>3-5yrs</td>
<td>3</td>
<td>40 or 100</td>
<td>3</td>
<td>.075</td>
</tr>
<tr>
<td>BAT</td>
<td>DP CPA Tm:YLF</td>
<td>3</td>
<td>Medium</td>
<td>5-7yrs</td>
<td>30</td>
<td>40 or 100</td>
<td>300</td>
<td>.75</td>
</tr>
</tbody>
</table>
• Questions?
• Postdoc?
• Job?

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