Next Generation Laser for Inertial Confinement Fusion


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Next-Generation Laser for Inertial Confinement Fusion


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ABSTRACT

We are in the process of developing and building the “Mercury” laser system as the first in a series of a new generation of diode-pumped solid-state Inertial Confinement Fusion (ICF) lasers at LLNL (see Fig. 1 below). Mercury will be the first integrated demonstration of a scalable laser architecture compatible with advanced high energy density (HED) physics applications. Primary performance goals include 10% efficiencies at 10 Hz and a 1-10 ns pulse with 1ω energies of 100 J and with 2ω/3ω frequency conversion.

BACKGROUND

Over the past 20 years LLNL has pursued the development and use of high energy lasers for target physics experiments in support of inertial confinement fusion (ICF). The technology upon which this effort has been based is the flashlamp-pumped Nd:glass laser. More than 30 years have elapsed since the first flashlamp-pumped Nd:glass laser was demonstrated, and this technology approach will soon culminate with the construction of the National Ignition Facility. Flashlamp-pumped Nd:glass lasers have offered crucial advantages (e.g. flexibility in pulse format, wavelength, and spectral width), allowing the progress in ICF physics that has been achieved to date. The slow shot rate of once every few hours, however, limits the number and type of experiments and applications that can be pursued. This limitation need no longer be imposed by the laser technology as first conceptually assembled in the early 1980s by Krupke and Emmett.1-2 The continuing effort outlined herein will culminate with the development of a new class of high repetition-rate fusion lasers and will produce the first rep-rated solid-state fusion laser facility (see Fig. 1 below).

The diode-pumped solid-state laser (DPSSL) ICF-driver concept has the important advantage of direct connectivity to NIF and past Nd:glass solid-state lasers such as Nova and Beamlet. The common technical issues with all solid-state lasers such as nonlinear propagation, beam-smoothing, and energy storage, are numerous; on the other hand, in order to achieve the high rep-rate and efficiency envisioned for this new

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generation of lasers (10 Hz repetition rate and 10% efficiency, respectively) it is necessary to replace the flashlamps with semiconductor laser diodes. These systems will be capable of repetition rates up to 10 Hz, which are more than three orders of magnitude higher than those of typical fusion lasers today. Mercury will produce 100 Joules/pulse that will provide “shots-on-demand” for users. This higher rep-rate laser system could be utilized by constructing multiple specialized use target chambers and multiplexing the rep-rated laser between them. A high rep-rate laser driver will also ultimately be needed if ICF is to provide a means of generating electrical energy.\textsuperscript{2,3} The data in Fig. 1 below depict the progress in the energy of ICF lasers built at LLNL, and how the proposed effort in diode-pumped solid state lasers is only in its infancy at this time. The proposed Mercury facility will move this technology forward by two orders of magnitude in energy and will take us on the first significant step into this new generation of high energy density and inertial confinement fusion lasers.

Fig. 1. Conceptual diagram of Mercury laser system.
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TECHNOLOGY DEVELOPMENT

A significant part of our effort is being directed at component research and development for critical areas within the Mercury design such as diode fabrication and costs, crystal growth, and advanced cooling concepts. We describe the progress of these efforts in more detail below.

Laser Architecture and Modeling

We have assembled a preliminary design for the laser system as shown in Fig. 3. The laser design is predicated upon using a Yb-doped crystal (Yb-doped strontium fluorapatite, Yb:S-FAP) that offers better diode pump laser costs due to its long storage...
time, than the traditional Nd-doped glass gain medium. The laser system utilizes three subsystems for pulse amplification: a fiber oscillator, regenerative amplifier, and two power amplifiers. The final amplification stages are accomplished through four passes of the beam through two gas-cooled amplifier head assemblies. The reverser optics allow the beam to be injected and 4-passed through the amplifiers while preserving the image relaying without the need for an optical switch. A deformable mirror either placed at the end of the amplifier path (as shown) or within the reverser optics path will be used to correct for wavefront distortions incurred during amplification.

Fig. 4. Diode pumped amplifier head configuration.

A more detailed picture of the pumping geometry is shown in Fig. 4. The amplifier head will be optically pumped from both sides. The dual pumping design allows for more uniform pumping and thermal loading on the crystals. The light from the diode array light is first condensed with a lens duct followed by an optical element which homogenizes spatial profile of the pump beam. The light emerging from the output of the homogenizer is relay imaged onto the gain media with a pair of lenses. The angled dichroic beam splitters allow the pump beam to pass through the optic and into the amplifier head while allowing the extraction beam to be reflected.

We have performed an analysis of the laser system's performance as pictured in Fig. 5. This numerical evaluation includes: quasi-4-level saturated pumping and extraction (Frantz-Nodvik), St. Venant edge distortion effects, diode spectral chirp versus crystal absorption, radiation trapping, isotropic amplified spontaneous emission (ASE), lifetime-induced pumping losses, thermal fracture limits, gas-cooling flux limits, laser damage thresholds, B-integral limitations, and multipass gain in the amplifier with longitudinal and temporal finite elements. The results of exercising the code are shown below in Fig. 5. For a nominal operating pump pulse width of 1 ms the predicted energy output is over 100 J with an optical to optical efficiency of 24%.
Diode Arrays
Laser diode arrays represent a critical technology for realizing inertial fusion energy. Not only are the diode technical performance specifications for inertial fusion energy (IFE) more demanding than what is currently possible using existing technology, but the diode array manufacturing costs will have to be reduced by at least two orders of magnitude to make IFE economically viable. Today, most of the cost associated with fabricating laser diode arrays is attributed to "packaging." What is especially challenging is that higher performance or brightness must be achieved while simultaneously reducing cost. We believe the diode array design described below offers significant advances in both areas.

<table>
<thead>
<tr>
<th>PRIMARY GOALS</th>
<th>Mercury goals</th>
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<tbody>
<tr>
<td>Scalable architecture</td>
<td>Yes</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>10 Hz</td>
</tr>
<tr>
<td>Efficiency</td>
<td>10%</td>
</tr>
<tr>
<td>Energy</td>
<td>100 J</td>
</tr>
<tr>
<td>Beam quality (times diffraction limited)</td>
<td>5X DL</td>
</tr>
<tr>
<td>Frequency conversion</td>
<td>50% efficiency</td>
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<tr>
<td>SECONDARY GOALS</td>
<td></td>
</tr>
<tr>
<td>Target shooting facility</td>
<td>Yes</td>
</tr>
<tr>
<td>Retrofittable for short pulse operation (10 ps)</td>
<td>Not precluded for future retrofit</td>
</tr>
<tr>
<td>Full aperture switch</td>
<td>Conceptual design</td>
</tr>
</tbody>
</table>
We have successfully fabricated and tested 10 bar array thus far. The array was operated up to 1 kW of peak power (100 W/bar) and all of the bars performed similarly. This array was life-tested with encouraging results since there was no apparent degradation after $10^9$ shots under Mercury operating conditions. Collimation of the emerging diode light has been successfully demonstrated using cylindrically shaped fiber lenses. The output divergence was measured to be $< 85$ mrad with 85% collection of the output.

During pulsed operation the diodes undergo a thermal transient which results in a power drop during the pulse and shift in the output wavelength. To better understand these issues we have simulated the performance of the diodes to account for these effects (see Fig. 6). Our baseline design for Mercury uses several 40-bar tiles ($4 \, \text{cm} \times 1 \, \text{cm}$). The heatsink design will continue to be optimized in several ways to meet the Mercury requirements, such as diode cavity length and metalization process.

Crystal Growth

The goals of the crystal growth efforts for the Mercury project are to assess the growth potential of Yb:S-FAP [Yb$^{3+}$:Sr$_5$(PO$_4$)$_3$F] crystals, develop an outside company resource for the growth of full size crystals, and investigate the capability and integrity of the fusion bonding process to attach the cladding layers for large scale crystals ($3 \times 5 \times 0.75 \, \text{cm}$).

The final composite crystal assembly is shown in Fig. 7, where seven of these crystal assemblies will be employed in a single amplifier head. Yb:S-FAP crystals are typically grown by the Czochralski method. At present, small high quality, crystals (2 cm diameter x $\sim 3$ cm length) have been grown with absorption and scatter losses $< 0.3\%$/cm. Mercury crystal apertures however, are much larger in comparison making crystal growth more challenging, and therefore, high optical quality material of the appropriate dimensions is not yet available.
Recent results indicate that we are on the right path to understanding and solving the defect problems in large scale crystal growth of Yb:S-FAP. Four possible defect structures can be seen in Yb:S-FAP: cloudiness, core defects, domain structures, and cracking. Detailed plans are in place to address each of these defect problems. We have grown a 5.1 cm dia. x 1.5 cm thick crystal from which a 2.2x1.8x1.0 cm clear crystal was obtained as shown in Fig. 8. The significant progress made to date makes us confident that growing large aperture, high-optical quality crystals for the Mercury Laser will become practical.

**Fig. 7 Composite crystal assembly**

**Fig. 8 Picture of new Yb:S-FAP crystal**

**Thermal Management**

The Mercury laser head and gas cooling architecture is being designed in a modular fashion, for which the laser slabs are mounted in a vane element, as shown in Fig. 9. The vane elements are then stacked to form the laser head assembly, a cross-section of which is depicted in Fig. 10. Between each of the flow vanes is a cooling channel to
remove the waste heat from the laser slabs. Upstream of the constant area channel section are nozzle elements where the helium cooling flow is accelerated to Mach 0.1. Downstream of the channel section are diffuser elements (both in the vanes and in the containment structure) where the flow is decelerated.

Fig. 9. Composite crystal assembly embedded into cooling vane structure

Fig. 10. A schematic of the cross-section of a Mercury laser head showing the stacked vane structure with yellow cooling channels between each vane.

A key element in the cooling flow design are the diffuser elements downstream of the channel region. The design must eliminate the flow “separation,” a detrimental effect which results in flow induced vibration of the laser amplifier head. To establish the proper diffuser design, calculations have been performed using a fluid dynamics code. We are in the process of designing and implementing a three-vane prototype flow test fixture, as described in Fig. 10 to validate our understanding of these complex flow effects. All the key elements of the Mercury cooling flow design will be explored in this test.
SUMMARY

The Mercury Laser is intended to serve as the next-generation fusion laser at LLNL. Flashlamp-pumped Nd:glass systems have served as a central technology by which the physics of ICF and high energy density plasmas have been explored over the last two decades. Laser technology has progressed, however, such that it is now possible to envision systems that are not repetition-rate limited, and have much greater reliability. This DPSSL technology would also serve as a prototypical design of an ICF driver for energy production.

There are significant technical challenges incorporated into the Mercury development plan that will advance key elements of laser technology by orders of magnitude. For example, we will advance the scale of the diode array peak output powers to ~1 MW, and simultaneously increase the brightness by 2X over that typically available from commercial diode arrays. This effort will also develop the largest Yb:S-FAP crystals ever grown by a factor of six in volume. The gas-cooled-slab architecture will enable high peak power (up to TW) lasers to be extended to large output powers of up to >1 kW average power. In addition, this will be the highest energy/pulse diode-pumped laser ever built by an order of magnitude. These and other significant advances will make this project extremely challenging within the current scope of schedule and budget.

References:
