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Diode-Pumped Solid-State Lasers: Next Generation Drivers for Inertial Fusion Energy and High Energy Density Plasma Physics

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"Diode-Pumped Solid-State Lasers: Next Generation Drivers for Inertial Fusion Energy and High Energy Density Plasma Physics"

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I. ABSTRACT

We are in the process of developing and building a 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). This laser system named "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.

II. 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 (NIF). 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 due to long thermal recovery times, 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 .

The common technical issues with all solid-state ICF 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 generation of lasers (10 Hz repetition rate and 10 % efficiency, respectively) it is necessary to replace the flashlamps with semiconductor laser diodes. Laser diodes offer high efficiencies (up to 50%) from their high overlap with the spectral absorption gain media thus generating less waste heat.

In addition to accelerating ICF target experiments, a high rep-rate laser driver will also ultimately be needed if ICF is to provide a means of generating electrical energy.[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 Laser will take us on the first significant step into this new generation of high energy density and inertial confinement fusion lasers.

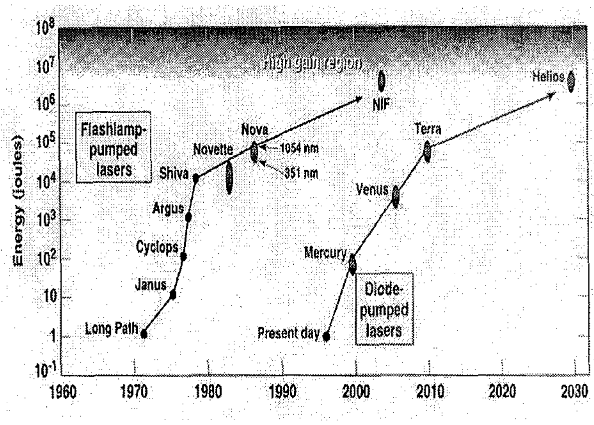

Fig. 1: Plot of the energy from flashlamp-pumped Nd:glass lasers as a function of time, and the potential time-line for diode-pumped laser development.

III. MERCURY LASER ARCHITECTURE

We have assembled a preliminary design for the laser system as shown in Fig. 2. The laser design is predicated upon using a Yb-doped crystal,[4,5,6] (Yb-doped strontium fluorapatite, Yb:S-FAP) that offers better diode pump laser costs due to its ~4x longer 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..

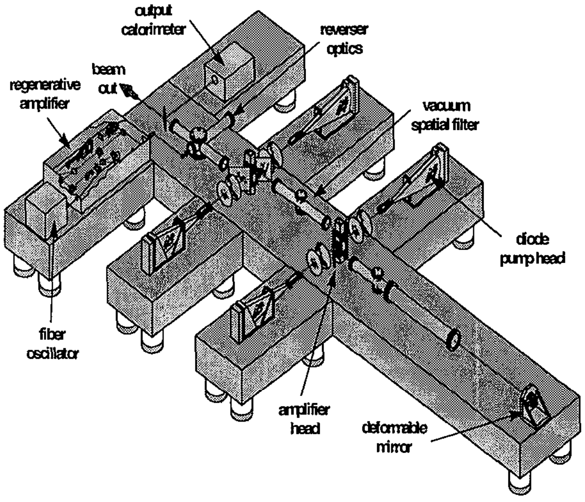

Fig. 2. Mercury laser system layout.

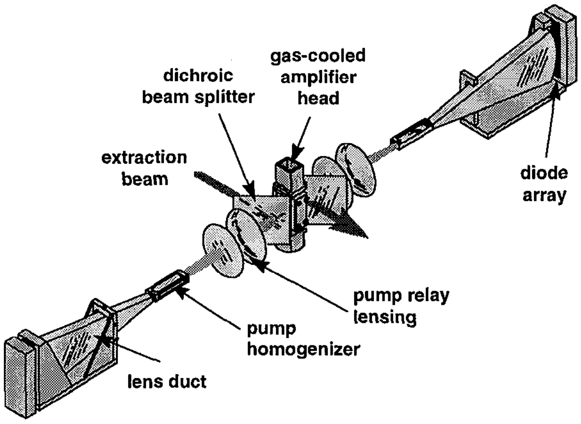

Fig. 3. Diode pumped amplifier head configuration.

A more detailed picture of the pumping geometry is shown in Fig. 3. 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. 4. 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. 4. 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% or >10% electrical-to-optical efficiency.

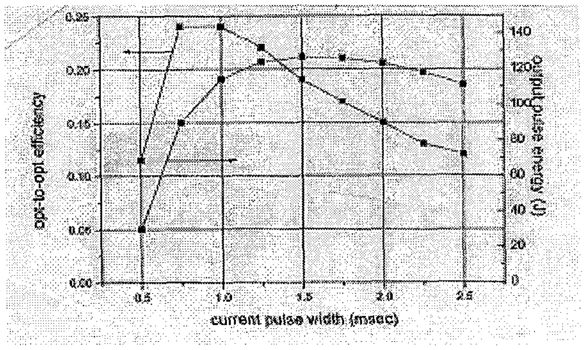

Fig. 4. Modeled laser output energy and efficiency plot as a function of the pump time

IV. DRIVER FOR ADVANCED EXPERIMENTS AND INERTIAL FUSION EXPERIMENTS

The Mercury laser should be viewed as the first small but significant step toward the emergence of a new technology paradigm for fusion laser drivers. The flashlamp-pumped Nd:glass lasers used since the 1970's have proved invaluable for unraveling the plasma physics and target issues relating to achieving fusion ignition. The success of the solid state laser follows from the fact that this approach is inherently "engineerable" and able to meet the demands on pulse shaping, wavelength, power balance, etc.

imposed by the target physics. The concept of an inertial fusion power plant is thought to require a ~4 MJ laser driver with >10% efficiencies. In a sense, the laser driver is one of the more developed technologies of inertial fusion energy (IFE), since other areas such as the survivability of the "final optic" (separating the laser for the target chamber) and the first wall (which encounters the x-ray and target debris following implosion) have not yet been resolved. Other pressing issues involve chamber clearing and target fabrication/injection as well as the need for beam smoothness and bandwidth on the laser driver. The success of laser-IFE will ultimately require the resolution of the fusion physics, laser driver, chamber recovery and survivability, and economic issues.

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