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Next-generation laser for inertial confinement fusion *

Development of diode-pumped lasers designed to produce 100-J at 10-Hz with 10% efficiencies for a new generation of inertial confinement fusion lasers is described

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ABSTRACT

We report on the progress in 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 Lawrence Livermore National Laboratory (LLNL). 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 (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, 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 Nova include 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. 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 will take us on the first significant step into this new generation of high energy density and inertial confinement fusion lasers.

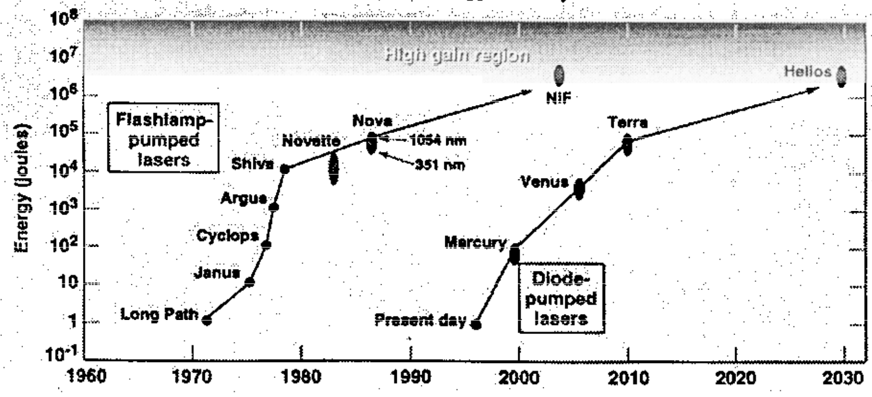

Fig. 1: Plot of the energy from flashlamp-pumped Nd:glass lasers as a function of time, and the potential time-line for diode-pumped laser development.

TECHNOLOGY DEVELOPMENT

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A significant part of our effort is being directed at component research and development for critical areas within the Mercury design such a 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

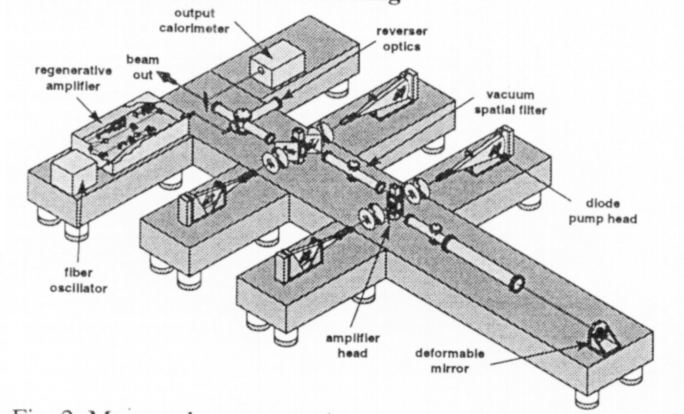

Fig. 2. Mercury laser system layout.

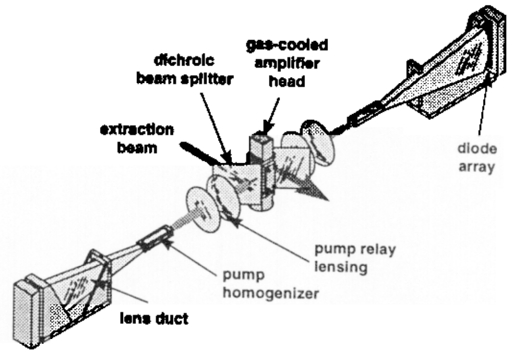

Fig. 3. Diode pumped amplifier head configuration.

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,[4-6] (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.

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. 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%.

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 in detail in another ASSL conference paper by Skidmore et. al. offers significant advances in both areas.

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+}:$Sr_5(PO_4)_3F$] 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 x 5 x 0.75 cm). The final composite crystal assembly consists of seven 4x6x0.75 cm slabs for each of the amplifier heads. Yb:S-FAP crystals are typically grown by the Czochralski method. At present, small high quality, crystals (2 cm diameter x ~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. This work is described in more detail in another ASSL abstract by Schaffers et. al.

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[7-8]. The vane elements are then stacked to form the laser head assembly, a cross-section of which is depicted in Fig. 4. 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. To establish the proper diffuser design, calculations have been performed using a 3D fluid dynamics code.

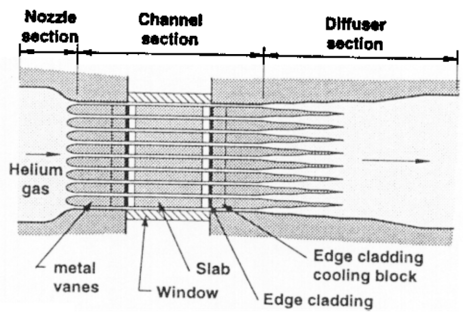

Fig. 4. A schematic of the cross-section of a Mercury laser head showing the stacked vane structure with yellow cooling channels between each vane.

SUMMARY

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.

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