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DIODE-PUMPED SOLID-STATE-LASER DRIVERS AND THE COMPETITIVENESS OF INERTIAL FUSION ENERGY

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ABSTRACT

Based on five technical advances at LLNL and a new systems-analysis code that we have written, we present conceptual designs for diode-pumped solid-state laser (DPSSL) drivers for Inertial Fusion Energy (IFE) power plants. Such designs are based on detailed physics calculations for the driver, and on generic scaling relationships for the reactor and balance of plant (BOP). We describe the performance and economics of such power plants, show how sensitive these results are to changes in the major parameters, and indicate how technological improvements can make DPSSL-driven IFE plants more competitive.

1. INTRODUCTION

The results of recent conceptual studies^{(1),(2)} suggest that a diode-pumped solid-state laser (DPSSL) might be a viable driver for an IFE plant. To more thoroughly assess the technical and economic feasibility of using such a driver, we developed a detailed physics-analysis code DPSSLIFE⁽³⁾ in Microsoft QuickBASIC that optimizes parameters to minimize the expected cost of electricity (COE). We then conducted a study that considers the significant physics and system details that might affect both the development path of a DPSSL and the resultant COE. An overview of the results is presented here; details will follow in future reports.^{(3),(4)}

Five technological advances at LLNL permit the design of a credible DPSSL driver for IFE at this time: efficient laser-diode pump sources,⁽⁵⁾ gas-cooling systems to adequately cool laser slabs,⁽⁶⁾ continuously annealed (heated) fused-silica final optics,⁽⁷⁾ a novel laser gain medium Yb^{3+} -doped $\text{Sr}_5(\text{PO}_4)_3\text{F}$ [Yb:S-FAP],⁽⁸⁾ and a large-aperture gas-cooled Pockels cell.⁽⁹⁾ Based on these advances, we developed a laser driver design that appears to be a viable IFE driver. To concentrate on the driver aspects and to compare our results with earlier IFE driver studies, we did not consider the reactor and the balance of plant (BOP) in any detail. We treated them as two separate lumped units whose features and costs are based on a summary of the details published for the KrF-driven Sombrero concept.⁽¹⁰⁾

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2. THE DPSSL DRIVER

2.1 Overview of Laser and Plant Operation

The overall operation of a 1-GWe plant using our baseline driver design employing a multipass regenerative amplifier configuration (Fig. 1) is as follows. About 28% of the gross electric power is recycled and conditioned with 95% efficiency to operate 60%-efficient diodes producing about 1 kW/cm^2 at 900 nm wavelength. The output of these diodes is concentrated to deliver approximately 11 kW/cm^2 at normal incidence to pump the laser crystals through the regenerative amplifier end mirror. After the Yb:S-FAP laser crystals are pumped for 1.0 ms to a stored-energy density of 0.8 J/cm^3 , a laser beam at 1047 nm wavelength is injected from the front end into the regenerative amplifier spatial filter. This beam completes four passes in the cavity, extracting the stored energy with 70% efficiency. Then, the plasma-electrode Pockels cell is energized to rotate the plane of polarization, and the beam reflects off the inclined polarizer and exits the regenerative amplifier. Subsequently, the light is spatially filtered to remove accumulated nonlinear distortions, frequency tripled from 1ω (1047 nm) to 3ω (349 nm) in a gas-cooled harmonic converter, and guided by turning mirrors to a final focusing lens and through a pair of fused-silica wedge optics to the target. In our baseline design, about 3.6 MJ of usable energy is delivered into the target, which implodes and burns releasing about 265 MJ of fusion energy (68% is in the form of 14 MeV neutrons and 32% is in the form of x rays and plasma debris). The neutrons deposit their energies throughout the reactor blanket, adding 8% more heat energy through $(n, 2n)$ reactions. The x rays and plasma debris are absorbed in the front face of the blanket (i.e., the first wall). Coolant fluid flowing through the blanket extracts the fusion heat, usually through intermediate heat exchangers (to avoid tritium contamination of the final heat-cycle components), to drive turbine generators. The overall thermal-to-electric conversion efficiency is assumed to be 45%.⁽¹⁰⁾

FIGURE 1. Multipass regenerative amplifier configuration.

2.2 Diode Pump Sources

The technology for mass producing laser-diode pump arrays has progressed rapidly. During the past few years, R. Solarz et al.⁽⁵⁾ at LLNL have developed a suite of processes to manufacture high-average-power pump arrays. Using the rack-and-stack 2-D architecture, the direct unit cost to produce cw arrays is about \$1/peak watt at LLNL (excluding overhead and profit). Analysis of technical and manufacturing cost-center data indicates that, by adopting a new monolithic 2-D array architecture presently under development at LLNL, it should be possible to realize a direct unit cost of a few cents/peak watt in a sustained IFE power-reactor-scale market of >1 GW/yr. After including the mark-up and capitalization costs, we conclude that a *price* of 7 cents/peak watt is a rational goal.

2.3 Gain Media

Table 1 compares the approximate requirements of the gain medium for a DPSSL with the properties of Yb:S-FAP. As noted in the last column, Yb:S-FAP meets or exceeds all of the criteria imposed by IFE requirements. Many other crystal properties are important including the thermal, mechanical, and optical properties of the S-FAP host (e.g., thermal conductivity, thermal-expansion coefficient, and the change of refractive index with temperature). Yb:S-FAP meets or exceeds all of these criteria as well. The Yb:S-FAP crystal can also be grown in large sizes with high optical quality using conventional melt-growth techniques.

Table 1. Comparison of the minimum and preferred properties of the gain medium with the values attained by Yb:S-FAP.

Criterion	Minimum	Preferred	Yb:S-FAP
Storage lifetime (ms)	1.0	>3	1.26
Extraction cross section (10^{-20} cm ²)	1.5	3 to 7	7.3
Limiting extraction efficiency	0.8	>0.9	0.96
Compatibility with efficient pump source	Diode laser	AlGaAs or InGaAs diodes	InGaAs

2.4 Pumping Dynamics and Configuration of Gain Medium

The layout of the laser includes one set of laser crystals at each end of the regenerative amplifier. Each crystal set is made long enough to obtain the desired absorption of pump light, and to allow subdivision into slabs for adequate gas cooling of the large faces at the optimal doping. Each of the slabs is sectioned transversely into 15 subslabs (Fig. 2) to reduce the amplified spontaneous emission (ASE) losses. The optimal shape of these subslabs is rectangular to account for the inherent gain anisotropy of Yb:S-FAP (i.e., to make the product of ASE gain and path length the same for both transverse directions). Each subslab includes an unpumped insulated zone (Fig. 3) so that the typical peripheral (St. Venant) optically distorted border region arising from strains caused by near-edge thermal gradients can be reduced to at least half of its normal value.^{(3),(4),(11)} Such a configuration increases the "fill factor."

Except for a few approximations relating to the treatment of ASE, our code employs the exact pumping equations, so the initial stored energy density is obtained as a function of position in the crystal. By employing pump-light reflector mirrors in the regenerative amplifier, we increased the pumping efficiency from 50% to 58%. About 29% of the 11 J/cm^2 of incident pump light is lost to normal emission (i.e., fluorescence) during pumping, 9% to ASE, 4% to transmission, and the remaining 58% is stored.

2.5 Extraction

Extraction is handled in the code by tracing light sequentially through each optical component for four passes of the regenerative amplifier and then out to the final optic. The code accounts for the bulk losses ($0.05\%/cm$ for Yb:S-FAP and SiO_2 ; $0.4\%/cm$ for KDP in the Pockels cell; and $0.5\%/cm$ for KDP in the harmonic converter) and surface losses at every optic (generally 0.2% per surface, but 0.5% per surface for the harmonic converter). The energy stored in the laser gain medium is extracted by finding the input fluence that maximizes the final laser output fluence subject to constraints on B-integral, optical damage, and first-to-last photon gain ratio, the latter generally being the most constraining. For the case of a 1 GWe plant, the regenerative amplifier total loss per pass is 15%, the first-photon gain per pass is about 19, and the extraction efficiency is 70%.

2.6 Gas Cooling of Optical Crystals

Our scheme to cool the laser crystals is based on the gas-cooled-slab (GCS) technology.⁽⁶⁾ This technology has been experimentally verified and demonstrated to provide management of temperature gradients such that no significant thermally induced optical distortions will be generated other than a simple beam steering. Analytic equations have been developed based on the heat power input to the crystals, the maximum beam steering to be permitted, and the gas kinetics. These equations specify how a gain medium should be divided into sections separated by cooling gaps to avoid thermal fracture and to minimize the power consumed to cool the crystal. This method requires that the gas be turbulent and preheated prior to entering the gaps for a preheat length sufficient to establish a thermal boundary layer. We extended their methodology to the crystal array of Fig. 2 without detailed accommodation of the perturbing effects of either the edge claddings or the subslab mounts. Although these effects are expected to be minor with suitable design considerations, the methodology as applied to our specific configuration must be experimentally verified to prove its applicability. The details are presented elsewhere.^{(3),(4)}

2.7 Final Optics Design

The final optic will be a planar array of fused-silica wedgelets that correspond to the way a beam is divided into subbeams by the subslabs (Fig. 2). The wedgelets are inclined at Brewster's angle and heated to a temperature of 400°C to anneal neutron-generated color centers.⁽⁷⁾ Without this continuous annealing, fused silica would deteriorate in hours at any practical distance from the target, because optical degradation at 3ω has been measured to begin at about 10^{16} neutrons/cm².⁽¹²⁾

We placed the final optic at a distance from the target-chamber center based on various constraints.^{(3),(4)} For a 1 GWe plant, we found that the first wall of the reactor should be at a radius of 6.9 m, the final optic at 12 m, a second wedgelet array to remove chromatic aberrations at 17 m, the final focusing optic at 19 m, and the final turning mirror at 21 m.

2.8 Wavefront Distortions and Beam Quality

To describe how the beam quality of the whole laser is degraded by the combined wavefront distortions of its optics, we adopted a methodology being used for the Beamlet Project at LLNL.⁽¹³⁾ In particular, we considered the beam to be describable with a normal diffraction pattern at the target (i.e., with an Airy disc corresponding to the full aperture),⁽¹⁴⁾ but we enlarged the beam focus by an extra Airy-disc width for each additional one-third wave of distortion.⁽¹³⁾ The cumulative wavefront distortion is evaluated by coherently adding the distortion incurred from multiple passes through optics in the regenerative amplifier, and incoherently adding the distortion incurred from passage through other optics. The net result for an assumed $\lambda/30$ distortion for each optic in a 1 GWe plant is an imaging efficiency of 90% just to get the 3ω light into the target hohlraum entrance holes.

3. DPSSL POWER PLANT ECONOMICS

The cost of electricity in cents/kWh is given by

$$\text{COE} = \left(\frac{\text{FCR} \times \text{TCC} + \text{AC}}{8760 \alpha P_{\text{net}}} \right) 10^5 \quad (1)$$

where FCR is the fixed charge rate; TCC is the total capital cost of the whole plant; AC is the effective annual cost for operations and maintenance (O&M), decommissioning, and target fuels; 8760 is the number of hours in one year; α is the plant availability factor; and P_{net} is the net plant electric power in watts. We obtained total capital costs for items other than the diodes by multiplying the direct capital costs by the standard factor of 1.936.⁽¹⁰⁾

We based laser costs on the specifications shown in Table 2.⁽¹⁵⁾ We included a laser front end at a cost of \$1k/J to generate the optical pulse for injection into the spatial filter of the regenerative amplifier cavity.

Table 2: Laser Costs

Specification	Cost
Finished mirrors, lenses, and wedges	\$1/cm ²
Yb:S-FAP and KDP crystals	\$1/cm ³
Finishing of KDP crystals	\$1/cm ²
Finishing of other flats	\$0.50/cm ²
Purchase price of diodes (including indirect manufacturing costs)	\$0.07/peak W
Nonelectrical and control components in the Pockels cell	\$10/cm ²
Space frame to support the laser	\$45k/beamline
Miscellaneous beamline equipment	\$10k/beamline
Cooling equipment	\$1/W consumed in cooling
Power conditioning equipment	\$0.10/W

We used Sombrero⁽¹⁰⁾ direct-cost scalings for the reactor and BOP except we incorporated the option of multiple power units; scaled the cost of the reactor building with the first-wall radius; and included a separate target factory model with costs for equipment, a building, and O&M. We considered only three target gain curves (Fig. 4): a baseline curve,⁽¹⁶⁾ a Sombrero curve,⁽¹⁰⁾ and an estimate based on the Kidder model⁽¹⁷⁾ for the Fast-Ignitor target, an advanced concept being studied at LLNL.

FIGURE 4. The three target gain curves considered in this study.

4. RESULTS AND DISCUSSION

We optimized many designs using our systems code and deduced which system minimized the COE for given input conditions. Figure 5 illustrates how the COE is minimized for each of several major parameters. Our baseline design for a 1 GWe plant has minimum COE of 8.5 cents/kWh corresponding to a laser wall-plug efficiency of 10%. This result is somewhat higher than the future coal-fired plant estimate of 5.3–6.9 cents/kWh.⁽¹⁸⁾ It is not advisable to attach too much significance to projected COE as a figure of merit, however, because the underlying assumptions of different studies differ. We feel our results are conservative because they are based on laser technologies that have already been demonstrated.

FIGURE 5. Six parameters that are optimized for each design (arrows mark the minima).

For the Sombrero gain curve, we obtained 7.2 cents/kWh; considering the costs associated with our more detailed modeling, this result is essentially the same as the 6.45 cents/kWh reported for Sombrero.⁽¹⁰⁾ For the Fast-Ignitor gain curve, we obtained a COE of about 5.8 cents/kWh.

By running parameter studies, we found four parameters that have a significant impact on the COE when varied individually. Figure 6 reveals how the baseline COE of 8.5 cents/kWh can be significantly reduced with advances in any one of these four areas. If improvements are made simultaneously in more than one area, the reductions in the COE become even more significant.

Figure 7 shows the effect of using one driver to power many separate reactor and BOP units. These curves, based on a total capacity of 1 GWe, indicate that a utility may lower its total development costs by developing smaller (e.g., 250-MW) power units and bringing capacity on-line as needed. These advantages are in addition to the lowered risk that arises naturally from use of a DPSSL configuration because of its modularity and dual-use technologies.^{(3),(4)} Figure 8 illustrates the well-known decrease in COE associated with larger fusion power plants.

FIGURE 6. Four parameters have a significant impact on the COE (arrows mark the baseline values).

5. IFE COMPETITIVENESS

The most effective way to lower the COE for an IFE plant is to reduce the cost of the driver. According to Fig. 6, this can be done most effectively by achieving a target gain of ≥ 150 , and secondarily by achieving lower diode prices and gain media with storage lifetimes longer than 1.5 to 2.0 ms. For example, the baseline design has a total capital cost (TCC) of \$4.5B at 1 GWe, corresponding to 8.5 cents/kWh; the diodes, the rest of the laser, and the target factory account for 30.0%, 12.6%, and 4.0%, respectively, of this TCC. If the target gain is increased from 74 to 150 and no other changes are made, the TCC decreases to \$3.2B, the COE decreases to 6.4 cents/kWh, and the TCC fractions for the diodes and the rest of the laser decrease to 19.2% and 8.2% respectively. At this level of COE, the reactor and the BOP are each accounting for about one-third of the TCC, so effective decrease in the COE below this level must consider technological advances in these areas of the plant. For example, a replaceable (liquid) first wall can be used to increase the plant availability factor to at least 85%. Advanced methods to employ direct-conversion technologies in the BOP might also be considered.

If advances are made simultaneously in different areas of the plant, as Table 3 illustrates, DPSSL-driven IFE plants can become very competitive with future LWR and coal-fired plants (whose expected COEs range from 4 to 7 cents/kWh⁽¹⁸⁾). Note, however, that Fig. 6 and Table 3 show that COE decreases effectively only for a certain range of change in the parameters; further change (e.g., a target gain much above 150, or storage lifetimes beyond several ms) are not as effective in decreasing COE.

FIGURE 7. COE for multiple power units (totaling 1 GWe) using one DPSSL driver.

FIGURE 8. COE vs size of plant

Table 3: One illustration to show the advantage of achieving simultaneous technological advances in different areas of an IFE plant

Target Gain	Diode Price (\$/peak-Watt)	Plant Availability	COE (cents/kWh)
74	0.07	0.75	8.47
100	0.06	0.80	6.60
150	0.05	0.85	5.42
150	0.00	0.85	4.87
500	0.00	0.85	4.62

6. CONCLUSIONS

We developed an optimizing computer code to conduct detailed physics systems studies of arbitrary DPSSL architectures for an IFE power plant. The code treats the DPSSL systems with all of the important physics, but models the reactor and BOP as lumped units with costing based on the results published for the Sombrero concept. We believe our results demonstrate calculationally that the DPSSL is a credible candidate for an IFE driver. Final proof of this awaits experimental verification of the operation and cooling of a modular subunit of the laser, and experimental verification of the final-optic protection scheme. We displayed the expected nominal performance from our baseline laser design with a wall-plug efficiency of 10% and investigated how sensitive the results are to changes in the input parameters. This system study is a significant advance over previous conceptual studies of DPSSLs because the laser physics has been included at a substantially greater level of detail.

We expect the competitiveness of DPSSL-driven IFE plants to increase with future improvements in target gains, reduced costs of diode manufacturing, and the development of gain media with longer storage lifetimes. More competitive COEs can also be realized for multi-GWe plants, or for specialized advances in the reactor and BOP areas of the plant. We feel that future research will lead to engineering tests that will prove the viability of DPSSL drivers for IFE.

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