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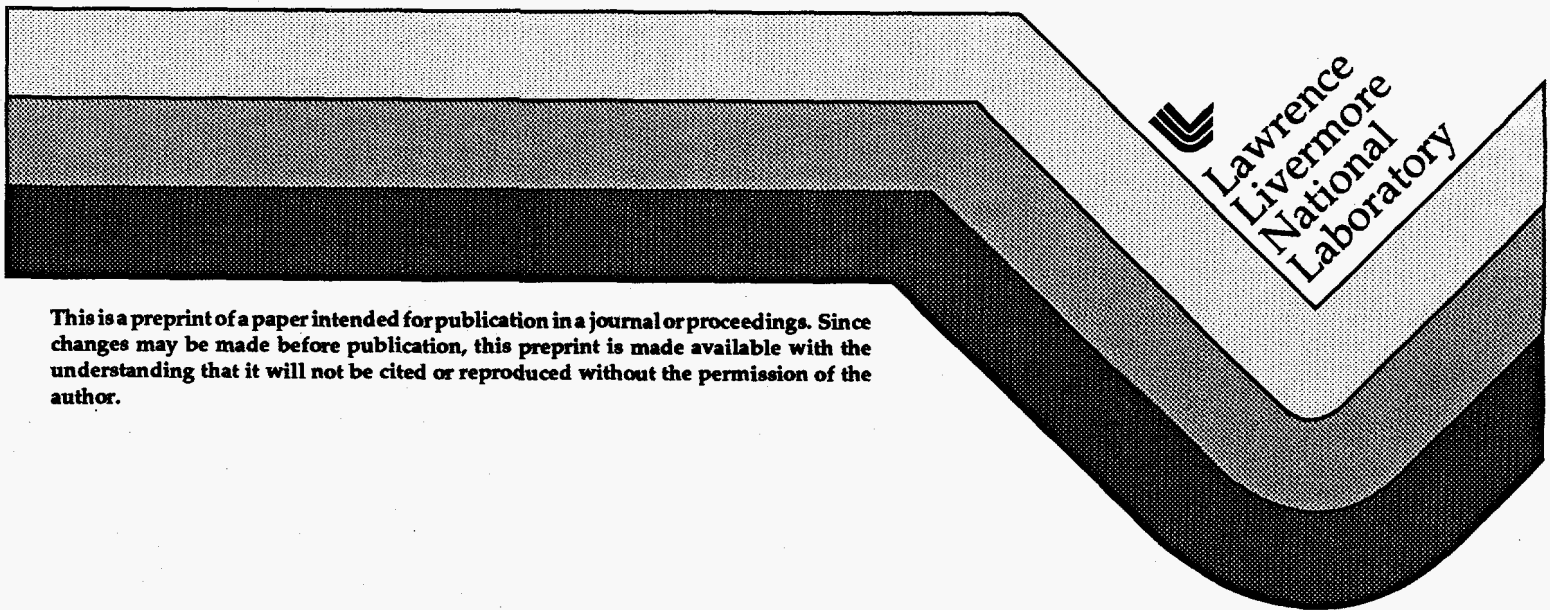
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## System Study of a Diode-Pumped Solid-State-Laser Driver for Inertial Fusion Energy

C. D. Orth  
S. A. Payne

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Lawrence  
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# System study of a diode-pumped solid-state-laser driver for inertial fusion energy

Charles D. Orth and Stephen A. Payne

Lawrence Livermore National Laboratory  
L-490, P. O. Box 808, Livermore, CA 94550-0808

## ABSTRACT

We present a conceptual design of a diode-pumped solid-state-laser (DPSSL) driver for an inertial fusion energy (IFE) power plant based on the minimized cost of electricity (COE) as determined in a comprehensive systems study<sup>1</sup>. This study contained extensive detail for all significant DPSSL physics and costs, plus published scaling relationships for the costs of the target chamber and the balance of plant (BOP). Our DPSSL design offers low development cost because it is modular, can be fully tested functionally at reduced scale, and is based on mature solid-state-laser technology. Most of the parameter values that we used are being verified by experiments now in progress. Future experiments will address the few issues that remain. As a consequence, the economic and technical risk of our DPSSL driver concept is becoming rather low. Baseline performance at 1 GW<sub>e</sub> using a new gain medium [Yb<sup>3+</sup>-doped Sr<sub>3</sub>(PO<sub>4</sub>)<sub>3</sub>F, or Yb:S-FAP] includes a product of laser efficiency and target gain of  $\eta G = 7$ , and a COE of 8.6 cents/kW·h, although values of  $\eta G \geq 11$  and COEs  $\leq 6.6$  cents/kW·h are possible at double the assumed target gain of 76 at 3.7 MJ. We present a summary of our results, discuss why other more-common types of laser media do not perform as well as Yb:S-FAP, and present a simple model that shows where DPSSL development should proceed to reduce projected COEs.

## 1. OVERVIEW

The inertial confinement fusion (ICF) community is searching for a driver for an inertial fusion energy (IFE) power plant that has low technical risk, low development cost, and practical economic value. Heavy-ion accelerators are often selected as the most potentially viable machine, although light-ion accelerators, KrF lasers, and other concepts are being considered. One difficulty in selecting the optimum concept at this time is our current lack of information concerning how well the various concepts will come to their proposed fruitions when fully developed in the future. Another difficulty is in dealing with different assumptions and limited analyses from various studies, because the complete systems-level picture of all aspects of the plant is desired. For example, a driver concept might be proposed as suitable, but there may not be an established concept for getting the driver beams focused reliably on the target, so the design of the plant as a whole may still have high technical risk.

Among the possible IFE driver concepts, there now appears a candidate that is significantly ahead of all others in terms of knowing how well the concept will ultimately turn out. This candidate is a diode-pumped solid-state laser (DPSSL), and it achieved this state because of a recent comprehensive systems study<sup>1</sup> that not only proposes solutions to the issues previously thought to limit the IFE application of lasers, but also represents a significant advance over previous conceptual studies of DPSSLs because it includes extensive detail of all important DPSSL physics. Because the driver physics has been included so completely, the key issues that remain for a DPSSL driver pertain to the extension of the parameter experimental base to the realm relevant for IFE, and to the particular use of the Yb:S-FAP gain medium. Near-term experiments that address these issues have already begun at LLNL, and some results are reported at this conference by C. Marshall. Further development of DPSSL parameters is required, of course, but less development is required for DPSSLs, and for less development cost, than for other concepts.

While few issues will remain for a DPSSL driver after the completion of experiments now in progress, there are significant issues relating to other areas of the plant, such as the selection of an acceptable target-chamber design that can accommodate a laser. In particular, an isotropic arrangement of beams entering a target chamber, or multiple cones of beams with large (40–70°) half angles, is not easily rendered compatible with first-wall concepts having high plant availability factors (e.g., liquid first walls). This issue, however, is directly associated with the amount of target gain, because smaller beam cone angles are possible with increased gain. Other important issues concern the alignment tolerances for target injection and tracking, the reduction of neutron damage thresholds due to the pulsed nature of ICF, and the protection of the final optics from x rays and plasma debris. Although a DPSSL can accommodate either direct or

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indirect (hohlraum) drive, there are issues concerning each of these target concepts, especially those relating to the smoothness of the laser irradiance for direct drive and the nature of the hohlraum plasma instabilities for indirect drive.

Therefore, although DPSSLs have not solved all of the problems, they have been developed to a point beyond other existing concepts in terms of the IFE operation of the driver itself. In particular, our design is supported by an existing experimental base for the delivery of high-power driver beams up to and into a hohlraum target. Only laser driver concepts (solid-state lasers and KrF) will have been developed to such an extent within the near future. Specifically, the DPSSL technology is based on the existing rather-mature technology for flashlamp-pumped Nd:glass lasers like Nova, and much of the DPSSL technology has already been experimentally verified by the Beamlet Project at LLNL, and additional verification is expected as the design for the National Ignition Facility (NIF) is developed. Our colleagues at LLNL have also verified many of the performance parameters for DPSSLs through dedicated experiments using diode-pumped Yb:S-FAP crystals.

The DPSSL concept does have an apparent economic limitation at this time, however, because our projected cost-of-electricity (COE) values of 6 to 9 cents/kW·h are larger than those published for many other driver concepts. This apparent difficulty is rendered moot, however, when one considers the different scopes of the various studies. We maintain that it is not fruitful to compare the results from different studies when there is not a common level of physics detail and/or optimism in the assumptions incorporated. Perhaps more importantly, our COE values are about twice the current economic rate. Such a disadvantage for IFE may remain unless significant improvements (especially in target gain) can be realized, because the cost of a driver facility is an added burden to an IFE plant that is not shared by conventional power sources.

Below we present a brief summary of our findings. We also explain why gain media more common than Yb:S-FAP do not perform as well as Yb:S-FAP for this DPSSL application, and indicate which improvements in DPSSLs will have the most effect in lowering the projected COE.

## 2. DPSSL PHYSICS AND COMPONENTS

### 2.1 Baseline laser architecture

Figure 1 shows the 4-pass laser architecture that we found best for optimizing the DPSSL performance.

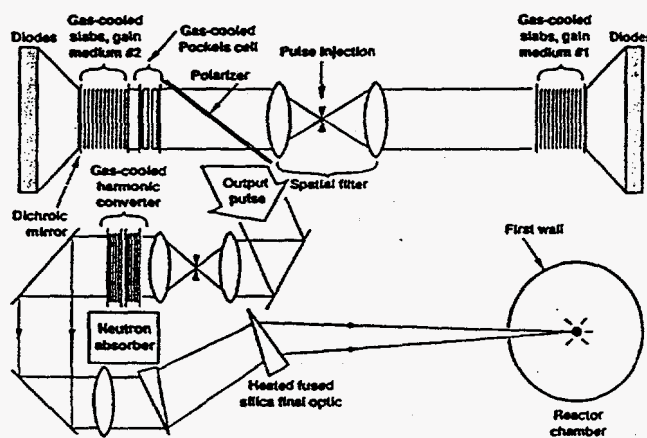


Fig. 1: One beam of the DPSSL multipass amplifier configuration (not drawn to scale).

For our 1-GW<sub>e</sub> baseline design, 31% of the gross electric power must be recycled and conditioned with 95% efficiency to operate 55%-efficient laser diode arrays producing about 1 kW/cm<sup>2</sup> at 900 nm wavelength. The output of these diodes is concentrated to deliver ~10 kW/cm<sup>2</sup> at normal incidence to pump the laser crystals through the end mirrors of the multipass amplifier. After the Yb:S-FAP crystals are pumped for 1.06 ms to a stored-energy density of 0.8 J/cm<sup>3</sup>, a laser

beam at 1047-nm wavelength is injected from the front end into the multipass spatial filter. The beam completes four passes in the cavity, extracting the stored energy with 70% efficiency (excluding a 88% fill factor). Then the plasma-electrode Pockels cell is energized to rotate the beam's plane of polarization, causing the beam to reflect off the polarizer inclined at Brewster's angle and exit the amplifier. After harmonic conversion to 349-nm wavelength with 80% energy-conversion efficiency, the beam is guided to a final focusing lens and through a pair of wedge-shaped final optics to the target. Combining 345 beams, 3.7 MJ of usable energy is delivered into a hohlraum target, releasing about 281 MJ of fusion energy (68% as 14-MeV neutrons and 32% in x rays and plasma debris). About 8% more energy is added to the neutrons through (n,2n) reactions in the chamber blanket. Based on the Sombrero study,<sup>2</sup> the overall thermal-to-electric conversion efficiency is 45%. The wall-plug efficiency of the DPSSL driver is 8.6% (although efficiencies twice as high are possible by optimizing quantities other than the COE).

Each 8.19-cm-thick Yb:S-FAP crystal (one at each end of the cavity) is divided into 11 slabs cooled by a 4-atm He-gas cooling system. Each laser slab, being about 57 by 62 cm, is subdivided (to reduce ASE) into 15 subslabs each with a pumped area of 10.0 by 16.6 cm. There are therefore about 5000 subapertures available for pulse stacking, if desired, to maintain an energy conversion efficiency during harmonic conversion of 80% even with a pulse shape starting with a low "foot." Not shown in Fig. 1 are the kinoform phase plates and adaptive optics that may be required to obtain the necessary beam spatial homogeneity. Also not shown is the intensity-smoothing hardware, which would probably utilize smoothing by multiple apertures (SMA) based on multiple beamlet wavelengths separated by 10 Å, but could alternatively utilize induced spatial incoherence (ISI) or smoothing by spectral dispersion (SSD).

## 2.2 Diode pump sources and gain medium

The output of semiconductor laser diodes at a peak power of 1 kW/cm<sup>2</sup>, although normally collimated to a FWHM of 60° in one direction and ~7° in the other, can be further collimated with cylindrical microlenses attached directly to the diodes to reduce the 60° divergence to <1°. The power density is then increased a factor of 10 by totally internally reflecting lensing ducts, which thereby increase the light divergence by a factor of 10 because of the conservation of radiance [W/(cm<sup>2</sup>sr)]. Taking these effects into account, as well as the "burn-in" degradation of the diodes and a measured duct efficiency >90% for a concentration of twice what we need, we estimate that future developments will permit an overall efficiency of 55% for the laser diodes, multiplied by a transport efficiency of 90% to account for the collective effects of the microlenses, the lensing ducts, and the transmission of the diode light through the cavity end mirror to the laser crystals.

The cost of laser diodes has been dropping with a "learning curve experience factor" of ~63%. At LLNL, using the rack-and-stack method, diodes can be made today for a direct unit cost that projects to ~\$0.50/peak watt assuming a sustained annual market of 3 MW/yr.<sup>1</sup> By adopting a 2-D monolithic architecture and by considering a sustained fusion economy of about (1 GW<sub>e</sub> plant)/yr, we estimate that the price (i.e., direct + indirect cost) of diodes will be ~7 cents/peak watt.<sup>1</sup>

Our selected gain medium is Yb<sup>3+</sup>-doped Sr<sub>5</sub>(PO<sub>4</sub>)<sub>3</sub>F, or Yb:S-FAP. This material is anisotropic, with different emission cross sections parallel (6.0–7.3×10<sup>-20</sup> cm<sup>2</sup>) and perpendicular (1.5×10<sup>-20</sup> cm<sup>2</sup>) to the electric field of the light wave. We find the effective absorption cross section to be 5×10<sup>-20</sup> cm<sup>2</sup>. The gain coefficient, laser damage threshold (~20 J/cm<sup>2</sup> at 3 ns), absorption bleaching profile, and many other optical and mechanical properties have been directly measured. As reported at this conference, our colleagues have already operated a subscale diode-pumped experiment using Yb:S-FAP crystals, and are soon to report results from a cooled-slab experiment.

We used our computer code to model pumping dynamics and extraction efficiency, using the precise physics equations applicable, including a model for amplified spontaneous emission (ASE). The gain medium has an intrinsic storage lifetime of 1.1 ms, which is lengthened by 985.3-nm zero-line radiation reabsorption to about 1.5 ms for our geometry. We subjected the extraction process to three constraints: B-integral less than 2 radians, a first/last photon gain ratio of 50, and various optical damage thresholds: 20(τ/4)<sup>0.35</sup> J/cm<sup>2</sup> for Yb:S-FAP, 16(τ/4)<sup>0.35</sup> J/cm<sup>2</sup> for the final optic, and 10(τ/4)<sup>0.35</sup> J/cm<sup>2</sup> for other optics except 10(τ/4)<sup>0.50</sup> J/cm<sup>2</sup> for KD\*P, all for pulse length τ in ns and a peak/valley fluence factor of [1.4+0.1(e<sup>AB</sup>-1)]. We used the detailed extraction equations for the quasi-four-level system. The crystal slabs are cooled by a turbulent flow of helium over the optical aperture, and we included the detailed cooling equations and thermal fracture stress limits (see Ref. 1 and its Refs. 28–32). This technology has been experimentally demonstrated at LLNL to manage temperature gradients in such a way that no significant thermally induced optical distortions are generated other than a simple beam-steering effect. We used similar treatments for the system to cool the Pockels cell

KD\*P crystals, and for cooling the harmonic-conversion crystals (where the latter included the equations for thermal dephasing). We also applied cooling systems to all heated structures and to the laser diode systems.

## 2.3 Final optics design

The final optic for each beam is a planar array of fused-silica wedgelets. The wedge angle is included so that upstream optics will not be directly exposed to fusion neutrons. The optic is heated to 400° C to anneal neutron-generated color centers.<sup>3</sup> Without this continuous annealing, the fused silica would deteriorate in minutes for our baseline design. We calculate at what distance to place the final optic based on mechanical constraints, steady-state transmissivity from neutron-induced discolorations, and heating from the absorption of both neutrons and 3 $\omega$  light (including the effects of gamma-ray production and the scattering of neutrons from nearby structures). For a 1-GW<sub>e</sub> plant, we place the first wall at a radius of 7.1 m, the final optics at 12.3 m, and the final focusing optic at 19.6 m.

## 2.4 Transport of 3 $\omega$ light to the target

We included detailed algebraic modeling of the collective effects of the optical wavefront distortions from all optics in transporting the 3 $\omega$  beams to the target as a function of the laser pulse length and hohlraum entrance-hole size required for any particular energy delivered into the hohlraum. We also included a closure model for the entrance hole, because it tends to close towards the end of the laser pulse. Rather than modeling noise sources, we assigned an extra diffraction-limited spot size for each additional one-third wave of optical distortion, allowing for the coherent addition of distortions for optics in the 4-pass amplifier.<sup>1</sup> Our baseline result, assuming  $\lambda/30$  distortion per optic, is a focused spot size 3.3 times larger than the 1 $\omega$  diffraction limit. This beam size causes a 10% loss in getting energy into the hohlraum.

## 2.5 Target gains

Coupling efficiency (i.e., the ratio of the capsule absorbed energy to the energy entering the hohlraum) was modeled algebraically, and varied from 11% to at most 20%, depending on the 3 $\omega$  laser energy  $E_{3\omega}$  entering the hohlraum. Based on input from J. Lindl and E. Storm, we used a baseline target gain  $G$  given by:

$$E_{3\omega} \text{ (MJ)} = 0.29298 + 0.046404G - 3.436 \times 10^{-4}G^2 + 5.94 \times 10^{-6}G^3 - 2.626 \times 10^{-8}G^4 + 3.8067 \times 10^{-11}G^5$$

Other gain curves are described in Ref. 1.

## 3. COST MODELING

The detailed cost scaling relationships are described in Sec. 3 of Ref. 1. Here we note that COE was computed using the standard method,

$$\text{COE} = 10^{-4} \left[ \frac{\text{FCR (TCC)} + \text{AC}}{8760 \alpha P_{\text{net}}} \right] \text{ cents/kW-h,}$$

where the fixed charged rate FCR (nominally 0.0967) and the plant availability factor  $\alpha$  (nominally 75%) are both functions of the net plant electric power  $P_{\text{net}}$  in GW, TCC is the total (direct plus indirect) capital cost, and AC is the annual cost for operations and maintenance (O&M) plus smaller contributions for decommissioning and target fuels. The cost scalings used for the target chamber and the balance of plant (BOP) were those used for Sombrero<sup>2</sup>, as modified as shown in Ref. 1. Some of the laser cost specifications from Ref. 1 are reproduced in Table 1 below:

**Table 1: Some Cost Specifications**

<i>Item</i>	<i>Cost Specification</i>
Diodes	\$0.07/peak W (price) \$0.002/peak W for field assembly
Mirrors, lenses, wedges	\$1/cm <sup>2</sup>
Yb:S-FAP and KD*P crystals	\$1/cm <sup>3</sup>
Finishing	\$1/cm <sup>2</sup> (KD*P) \$0.50/cm <sup>2</sup> (other flats)
Front end	\$15,000/J per beam line
Pockels cell (non-electrical components)	\$10/cm <sup>2</sup>
Each beam tube (excluding spatial filter hardware)	walls of 3 mm Al at \$2.50/lb; length of 5 × radius to final optic
Each spatial filter & components (excluding space frame)	f-15 optics and 6 mm stainless steel at \$5.00/lb, plus 50%
Space frame to support the laser	\$45k/beam line
Other beam line equipment	\$10k/beam line
Power conditioning equipment	\$0.1/W (average power)
Cooling equipment	\$5M(P <sub>cool</sub> /10 MW) <sup>0.6</sup>
Optics protection system	\$1M
Material cost per target	\$0.01
Amortization factor	1.936 (except diodes)

## 4. CALCULATED RESULTS

### 4.1 General results

We used our computer program to optimize the design by adjusting the parameters so as to minimize the COE. The code thereby set all dimensions, chose the number of slabs into which the Yb:S-FAP crystals must be divided for cooling purposes, set the parameters of the cooling systems, and determined the placement of all components (including the first wall and the final optics). The result was that a 1-GW<sub>e</sub> plant should run at about 11 Hz and have a projected COE of 8.6 cents/kW·h ( $\eta G \sim 6.6$ ) and a laser wall-plug efficiency of 8.6% (i.e., 8.6% of the total power needed to operate and cool the laser actually enters the target). Reference 1 lists the values of other parameters, and displays the sensitivity of the results to changes in various parameters. We find that the COE is only moderately dependent on the choice of (1) the price of the laser diodes, (2) the storage lifetime of the gain medium, and (3) the plant availability factor. In contrast, the results are highly dependent on the target gain, as revealed by Fig. 2 below.



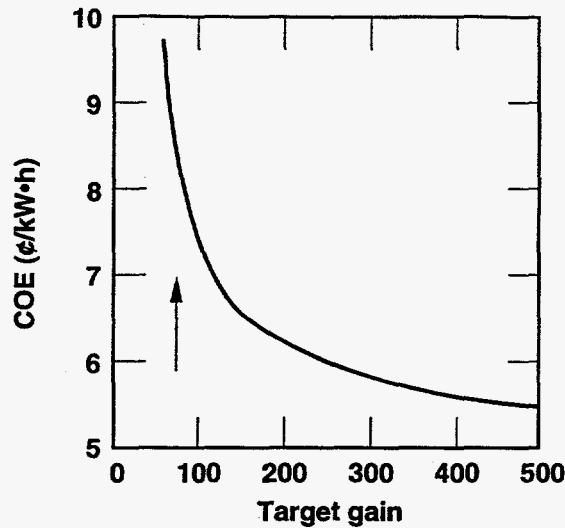


Fig. 2: Target gain has a significant impact on COE (arrow marks baseline value).

Note that the projected performance improves to 6.6 cents/kW·h if the baseline gain of 76 is raised to 150. In addition, significant improvements in overall laser efficiency are possible with further development of the laser diodes. For example, if the total efficiency to deliver diode pump light to the gain medium were 80% instead of our 50%, and if the price of diodes were only 3.5 cents/peak W, then our baseline design would have a total laser efficiency of 19% at 8.6 cents/kW·h (diode pump fluence = 30 kW/cm<sup>2</sup>, pumping time = 0.25 ms, pumping efficiency = 86%,  $\eta G = 13$ ,  $G = 69$ ).

## 4.2 Results for other gain media

Many other standard laser gain media can be considered for a DPSSL application, but the more common laser media do not appear at this time to be as well suited for this DPSSL application as Yb:S-FAP is. We reached this conclusion by running our systems code with a detailed specification for each of the materials listed below in Table 2. This table displays the preliminary optimized code results for minimum COE values (in cents/kW·h) at 1 GW<sub>e</sub>, along with the specific plant direct costs (C) and other quantities. This table clearly shows that the COEs for other media are larger than that for Yb:S-FAP (see second row from the bottom).

## 4.3 Simple model for the COE

To discover why other gain media do not perform as well as Yb:S-FAP, it is helpful to develop a simple model for the COE. Although there are many ways to do this, we note that the COE can be expressed as a function of just 3 parameters: the product  $\eta G$  of the laser wall-plug efficiency and the target gain, the  $3\omega$  output energy  $E_{3\omega}$ , and the pumping duty cycle  $\nu \tau_{\text{pump}}$  (i.e., the product of the plant repetition rate and the diode pump time). If we evaluate the COE equation given in Sec. 3 for  $P_{\text{net}} = 1$  GW, it indicates that the COE is approximately equal to a constant plus 1.5 times the TCC in G\$. Using this approximation, the COE can be given by the following expression:

$$COE(1\text{ GWe}) \approx \left\{ 3.0 + \frac{1.7}{\left[1 - \frac{2.14}{\eta G}\right]} + \frac{120}{(\nu \tau_{\text{pump}})(\eta G) \left[1 - \frac{2.14}{\eta G}\right]} + 0.07 (E_{3\omega})^2 \right\} \text{ cents/kW}\cdot\text{h}$$

**Table 2: Preliminary Systems-Code Results For Various Gain Media**

Parameter	Nd: YAG	LG- 750*	Yb: YAG	Nd: SrF <sub>2</sub>	Er: YAG	Yb: YLF	Ho: YAG	Ho: YLF	Yb:S -FAP
Laser efficiency	.050	.073, 063	.044	.044	.029	.044	.035	.045	0.086
Target G	86.	75.6, 80.2	115.	90.	130.	110.	118.	100.	76.4
Rep. rate (Hz)	11.5	12.5, 11.6	5.0	11.5	4.9	5.8	5.6	7.7	11.1
Recycle power fraction	.50	.39, .42	.42	.54	.56	.44	0.51	0.47	0.32
C <sub>laser</sub> (\$B)	10.96	5.75, 6.03	4.74	4.23	3.00	3.28	2.12	1.16	1.64
C <sub>diodes</sub> (\$B)	8.39	5.32, 5.54	3.68	3.57	1.59	2.51	1.06	0.72	1.36
C <sub>target chmbr.</sub> (\$B)	0.92	0.77, 0.80	0.84	0.98	1.05	0.85	0.95	0.87	0.72
C <sub>BOP</sub> (\$B)	0.69	0.60, 0.62	0.62	0.73	0.75	0.63	0.70	0.66	0.56
E <sub>3ω</sub> (MJ)	4.26	3.64, 3.91	6.32	4.49	7.50	5.89	6.52	5.19	3.68
ηG	4.3	5.5, 5.1	5.1	3.9	3.8	4.9	4.2	4.5	6.6
vτ <sub>pump</sub>	3.8	4.3, 4.6	6.4	11.5	20.1	11.0	26.3	34.7	11.8
COE via code (cents/kW-h)	27.0	15.4, 16.1	14.9	14.7	14.0	12.4	11.6	8.96	8.63
COE via model (cents/kW-h)	22.3	15.1, 15.9	15.1	14.2	14.5	12.5	11.7	9.6	8.8

\* First entry refers to 875-nm pump, second entry to 803-nm pump.

In the above equation, the second term on the right is the non-constant part of the cost of the target chamber and the BOP (where  $2.14/\eta G$  is the recycled power fraction for a thermal-to-electric conversion efficiency of 45%, divided by 0.96 for a 4% auxiliary power fraction). The third term is the non-constant part of the cost of the laser diodes, and the last term is the non-constant part of the cost of the rest of the laser components. The first term (the minimum COE) is a collection of the constant terms, and shows that IFE may have difficulty achieving a COE less than 3 cents/kW-h at 1 GW<sub>e</sub>.

If we compare the last two rows in Table 2, we see that this simple model fits the results of the complex systems code to better than about 10%. When applied to Yb:S-FAP, this model shows that the major cost items are those for the target chamber, the BOP, and the laser diodes (i.e., the respective terms are  $3.0+2.5+2.3+1.0 = 8.8$  cents/kW-h). If we increase  $\eta G$  by 50% for this medium, the COE decreases to 7.5, but if we increase  $v\tau_{\text{pump}}$  by 50%, the COE decreases only to 8.0. Therefore, as one might have guessed, the best way to reduce the COE for our baseline design is to increase the efficiency of the laser and somehow develop more target gain (i.e., increase  $\eta G$ ). How such a result relates to the specific properties of the gain medium itself is not straight forward, but this result does help to clarify the importance of seeking target designs with higher gains. Perhaps more importantly, this result shows that the optimum design will result by minimizing the COE while *simultaneously* maximizing both  $\eta G$  and  $v\tau_{\text{pump}}$ .

For a more general picture, we have plotted our COE model in Fig. 3 below for a fixed driver energy of 4 MJ:

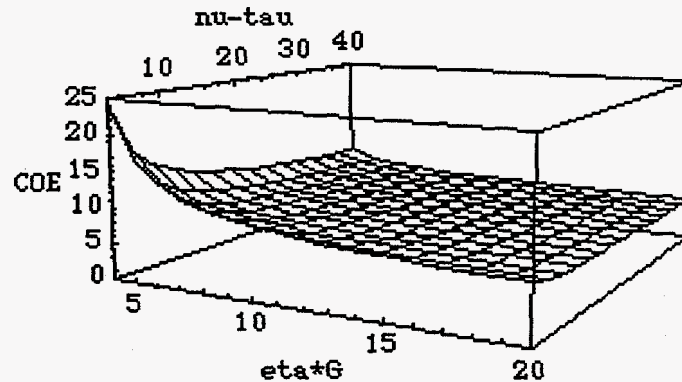


Fig. 3: Surface plot of COE model as a function of  $\eta G = \eta G$  and  $\nu\tau_{\text{pump}} = \nu\tau_{\text{pump}}$ .

Note that rather large COEs result for values of  $\eta G$  less than  $\sim 7$  or values of  $\nu\tau_{\text{pump}}$  less than  $\sim 10$ , but only gradual reductions in COEs result for values of  $\eta G$  greater than  $\sim 10$  or values of  $\nu\tau_{\text{pump}}$  greater than 15–20.

We can now use the above simple model to understand qualitatively why other gain media do not perform as well as Yb:S-FAP. Note from Table 2 that the  $\eta G$  values for many of these other gain media are  $< 5.5$  (typically  $\sim 4$ ) while the value for Yb:S-FAP is 6.6. The required laser energies for the other media are  $> 4$  (typically 4.5 to 6.5) MJ, while that for Yb:S-FAP is only 3.7 MJ. For Ho:YLF, these disadvantages are offset by a very high pumping duty cycle (35 ms), so its COE is not much more than that for Yb:S-FAP; however, it requires a larger recycled power fraction of 47%. The other media suffer from undesirable values in two or all of the 3 parameters of the model. Our simple model therefore shows why the common gain media are not as suitable as Yb:S-FAP for this particular application.

## 5. CONCLUSIONS

We have indicated that a DPSSL is one of the leading candidates that can serve as a driver for an IFE power plant. Of the significant issues that remain for a DPSSL-driven power plant, most of those relating to the DPSSL itself are being resolved by experiments already in progress or planned for the near future. Selection of a compatible target-chamber design will then be one of the key issues remaining. As far as the driver itself is concerned, a DPSSL uses more mature technology than other proposed concepts for an IFE driver. This status reflects the low technical risk and low development cost associated with a DPSSL driver. We have also shown that COE can be approximated by a simple algebraic model with only 3 parameters:  $\eta G$ ,  $\nu\tau_{\text{pump}}$ , and  $E_{3\omega}$ . Using this model, we indicated that our DPSSL design can be improved most readily by increasing  $\eta G$ , and specifically by realizing enhanced target gain. This model also helps explain why the more-common gain media are not as suitable for this application as Yb:S-FAP is.

## 6. ACKNOWLEDGMENTS

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