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Can solid-state laser technology serve usefully beyond fusion ignition facilities?

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ABSTRACT

We have explored the major technical and conceptual issues relating to the suitability of a diode-pumped solid state laser as a driver for an inertial fusion energy power plant. While solid state lasers have long served as the workhorse of inertial confinement fusion physics studies, the deployment of a driver possessing adequate efficiency, reliability, and repetition rate for inertial fusion energy requires the implementation of several technical innovations discussed in this article.

1. INTRODUCTION

The next major milestone for inertial confinement fusion (ICF) is to achieve ignition. The ignition experiments will define the target gain that is attainable. Since gain on the order of 50-100 is required for inertial fusion energy (IFE) to become economically viable, the target physics issues present the greatest challenge to the success of IFE. For example, questions concerning the use of direct versus indirect drive, and the repercussions of hydrodynamic and plasma instabilities, must be resolved. The proposed National Ignition Facility (NIF) is intended to address the crucial uncertainties in the target physics.¹ Although the ICF physics is the central issue at this time, a parallel path where the fusion chamber and driver are explored would provide broad-based progress in IFE.

The overall merit of a specific IFE driver involves a number of complex trade-offs among different criteria including: compatibility of target irradiation and stand-off requirements, cost and risk associated with the driver development, and the ultimate potential for efficiency and reliability. The important point is that each of the existing IFE driver options, including heavy ion, light ion, and laser drivers, offers a different balance among these criteria. A detailed comparison of the driver options is beyond the scope of this paper; in a sense it is also premature since the target gain has not yet been established. In any case, each driver option presents advantages and disadvantages. One of our key motivations for exploring the solid state laser option further is the benefit that can be derived from decades of research into solid-state fusion lasers — thereby reducing the risks associated with the driver performance.

Substantial innovations will nevertheless be required to progress from the low efficiency, low repetition rate flashlamp-pumped Nd:glass solid state lasers currently used, to the high efficiency and high repetition rate (re-rate) systems needed for IFE. Upon exploring the IFE requirements, we have identified four enhancements which would enable solid state lasers to service IFE objectives:

1. Replace the flashlamps with laser diodes
2. Substitute the Nd:glass gain medium with a higher thermal conductivity crystal (such as the recently discovered Yb:S-FAP).
3. Remove the waste heat from the gain medium slabs via their faces with a turbulent flow gas.

4. Heat the fused silica final optic so that the neutron-induced defects are rapidly annealed out.

Four additional papers in these Proceedings provide further technical detail on these activities and the solid state driver option.

The proposed diode-pumped solid state laser (DPSSL) design shares much with the existing flashlamp-pumped solid state laser (FPSSL) systems. The optical physics bears much in common, including pumping, extraction, pulse shape manipulation, nonlinear and linear wavefront distortion, amplified spontaneous emission losses, and frequency conversion. The DPSSL design draws heavily upon this extensive optical and laser physics base that has previously been elucidated. The experience with practical engineering aspects of fusion laser construction and operation are also beneficial, such as the fabrication of large area optics, optical damage considerations, beam alignment procedures, and mechanical design details. Low and medium-power DPSSLs are also entering the industrial and military arenas more broadly — for example in medicine, metal-working, remote sensing, telecommunications, illumination, and much more. This trend will undoubtedly continue, providing a synergism between energy objectives and the commercial and military sectors. The point is that although there are many technological challenges ahead, the environment is in many ways already supportive of our ambitious goals.

2. TECHNOLOGY AND ENHANCEMENTS FOR IFE

2.1 Flashlamps → diodes

The longevity, reliability, high efficiency, architectural flexibility, and low thermal loading of diodes now allow us to design DPSSLs suitable for IFE. The estimated number of shots required over the 30-year lifetime of the power plant with a driver operating at 10 Hz is about 10^{10} . Laser diode lifetimes are presently within reach of this goal. Low-power cw diodes are already being deployed undersea for telecommunications with anticipated 30-year operational lifetimes. Laser diodes offer high electrical-to-optical efficiency (up to 60%), and the output is both directional and monochromatic. The non-directional and spectrally broad (from UV to IR) output of flashlamps lead to less efficiency and flexibility compared to laser diodes. Laser diodes also offer reduced thermal loading in the gain medium compared to flashlamps (usually ~15% versus ~50% of the pump energy). In summary, diode laser pumping technology has changed the way scientists and engineers consider solid state lasers, as they apply to a wide variety of applications.

Another crucial feature is the cost of the laser diodes, a quantity that can be characterized in terms of dollars per peak watt. For our low duty factor application it is the peak pump power that is most relevant to the cost. This follows from the fact that the output power is limited by the facet damage threshold, which in turn is most impacted by the instantaneous power level.

Using several assumptions that render our cost analysis to be suggestive rather than quantitative, we can produce the plot shown in Fig. 1, based on information from internal LLNL operations.² (Costs include direct labor, benefits, yield, and materials, but specifically exclude profit, overhead, marketing, and equipment.) Figure 1 reveals that a precipitous drop in laser diode fabrication cost has occurred over the last few years, a trend that is also happening in the commercial sector to some extent.

We believe that diode costs could become as low as a few cents per watt when the many complex, tedious and labor-intensive steps are replaced by fully automated procedures. Presently, laser diode arrays are fabricated by individually producing one-dimensional bars and then arranging them into two-dimensional structures. Large cost reductions will demand the direct production of two-dimensional arrays, using fully-automated manufacturing techniques. With the enormous >1 GW power-level laser diode pump sources required for IFE power plants, laser diode arrays can become in effect a commodity. Based on judgment and extrapolation of learning curves, we believe

that a price of 7¢/watt (cost + profit) is a rational goal. While we cannot prove that our assertion is correct at this time, we note that experience with high-technology components such as computer chips is consistent with our expectations.

Fig. 1. Cost per watt for LLNL laser diode arrays as a function of year. See text for assumptions and details.

2.2 Nd:glass → Yb:crystal

The gain medium of choice for flashlamp-pumped solid state fusion lasers has long been Nd:glass, even since the 1960s. While improved glasses have continued to be developed — especially noting the shift from silicates to phosphates in the late 1970s — the essential features of the material have always been optimal for fusion lasers. In particular, Nd:glass offers multiple absorption bands that couple effectively with the spectrally broad output of flashlamps, relatively low cost for fabrication into large optics, and true four-level laser operation. With the emergence of laser diodes as the preferred pump source for IFE, it is sensible to reconsider the optimal gain medium.

As noted below in Table 1, we initially selected five rare earth laser ions as potential candidates.³ We then doped each ion into several common crystalline media (e.g. YAG, YLF, etc.) in order to infer a range of properties typically available for the categories denoted in Table 1. Only the Yb laser ion was deemed to have adequate features in all of these crucial categories. We then pursued a directed search among numerous specialized host crystals to identify the Yb-laser material that offers the best functional laser performance in realistic laser systems. Yb:S-FAP has emerged as this material of choice [i.e. Yb³⁺-doped Sr₅(PO₄)₃F].⁴⁻⁶

Ion	Storage lifetime (msec)	Emission cross section (E-20 cm ²)	Extraction efficiency (%)	Laser wavelength (nm)	Diode matl
Nd	0.2-1.3 ●	>1.3 ✓	<70 X	~1050 ✓	AlGaAs ✓
Yb	1-5 ●	0.1-6 ✓	<95 ✓	~1030 ✓	InGaAs ✓
Er	5-15 ✓	0.1-0.5 X	<90 ✓	~1630 ●	InGaAsP ●
Tm	5-15 ✓	0.1-0.5 X	<90 ✓	~1950 ●	InGaAsP ●
Ho	5-15 ✓	0.3-1.8 ✓	<75 X	~2100 ●	InGaAsP X

✓ Acceptable
● Marginal
X Not acceptable

Table 1. Survey of laser/spectroscopic characteristics of rare-earth-doped gain media.

Yb:S-FAP is well-matched to the output characteristics of laser diodes, in analogy to how Nd:glass is suited to flashlamp pump sources. Yb:S-FAP has a single ~ 4 nm wide absorption feature near 900 nm, and diode arrays can be processed to lase at this wavelength. Yb:S-FAP is distinguished from other Yb-based media in that its large pump and gain cross sections allow it to function effectively as a diode-pumped quasi-four-level laser,⁶ (e.g. it is straightforward to invert $>50\%$ of the Yb population). The gain cross section at $1.047\ \mu\text{m}$ of $6.0 \times 10^{-20}\ \text{cm}^2$ is similar to that of Nd:glass ($3.5 \times 10^{-20}\ \text{cm}^2$) assuring that the energy can be efficiently extracted. Importantly, the intrinsic lifetime of 1.1 msec is $>3\times$ that of today's Nd:glass (0.35 msec) allowing for more efficient storage of pump energy — leading to essentially a $>3\times$ reduction in the quantity of laser diode arrays that must be purchased. As stated previously, the cost of diodes is driven by the peak pump power required and for a given output energy that power scales inversely with medium lifetime. This point is crucial, since the diodes account for 31% of the cost of the plant. Finally, we note that we have grown Yb:S-FAP in relatively large size (4 inches $\times$ 1 inch $\varnothing$), with low scatter loss ($<0.1\%/ \text{cm}$), and high damage threshold ($>20\ \text{J}/\text{cm}^2$ at 10 nsec). In spite of the short amount of time and effort dedicated to Yb:S-FAP, its properties appear very promising for the IFE objectives.

Since Yb:S-FAP is an anisotropic crystal rather than a glass, its spectral properties are also anisotropic. In fact, although the gain cross section is $6.0 \times 10^{-20}\ \text{cm}^2$ along the laser polarization, we have found that it is only $1.5 \times 10^{-20}\ \text{cm}^2$ in the plane perpendicular to the laser polarization axis. The very low cross section in the non-lasing directions presents a special advantage for reduced losses arising from amplified spontaneous emission.

2.3 Convection cooling $\rightarrow$ forced turbulent flow cooling

Present Nd:glass fusion lasers operate as single-shot devices, while IFE goals call for a rep-rate of ~ 10 Hz. While gas flow is presently used in some Nd:glass systems to increase the rep-rate slightly (~ 1 shot/hour), a new concept is needed for IFE-like conditions.

By considering the basic structure of fusion lasers it is noticed that the largest surface area of the gain medium slabs tend to be the surface through which the laser beam passes. As a consequence, the heat will also need to be removed through this same surface, without distorting the light beam. We have found that this can be accomplished by way of helium gas-cooling, using a flow of about 0.07 Mach in a 3.6 mm channel, in order to remove the required $0.8\ \text{W}/\text{cm}^2$ of waste heat.

An off-line testbed and modeling study of the gas-cooled slab (GCS) concept⁷⁻⁹ has proved that the waste heat can be removed without slab fracture, excessive wavefront distortion, or significant optical scattering loss. The basic structure of the flow channel is pictured in Fig. 2, where the channel is seen to constrict in order to appropriately accelerate the flow. Effective thermal transfer entails the need for turbulent (rather than laminar) flow, and the evolution of the thermal boundary layer (see the article in the Proceedings by Sutton et al. for more detail). Once the thermal boundary layer becomes fully developed, the temperature rise in the flow direction is linearly related to the position along the slab. As a consequence, the optical distortion reduces to a simple beam steering effect that is amenable to a straightforward compensation.

Fig. 2. Schematic structure of flow channel employed to implement the gas-cooled slab concept.

2.4 Heated fused silica final optic

One of the challenging aspects of laser driven IFE is the fact that the so-called final optic will be irradiated by neutrons and gamma-rays emanating from the target chamber. The ionizing radiation is expected to induce color centers in the optical material that will reduce the transmission level of the ultraviolet (0.35 μm) third harmonic laser light which is presumably required for optimum target performance. We have developed a concept where the induced color centers of fused silica can be rapidly annealed away by holding the optic at an elevated temperature as first conceptualized by Woodworth, Chase and colleagues.¹⁰

In brief, we have found that the neutrons and gamma rays have different effects on the fused silica — neutrons create oxygen deficient centers (ODC or Si-Si bonds) which absorb at 246 nm, while gamma rays convert the ODCs to E' centers (which absorb at 210 nm). Both of these defects are annealed away at 300-500°C. The data in Fig. 3 shows the ODC and E' bands that are created, while the second spectrum was acquired after annealing the fused silica glass. It is noteworthy that the operating wavelength of the laser (0.35 μm) corresponds only to the tail of these absorption features. We have obtained extensive data on the effect of radiation-induced defects and their annealing

Fig. 3. Absorption induced by ionizing radiation in fused silica. Effect of annealing is also shown.

behavior, and have generated a kinetic model to calculate the steady-state absorption that is present (for various temperatures) at the IFE-relevant dose rate of 50 krads/sec (Fig. 4). It appears that temperatures on the order of 400-500°C will be adequate (see the article by Marshall et al. in this Proceedings for further details on this topic).

Fig. 4. Steady-state absorption occurring in fused silica as a result of irradiation of neutrons and gamma rays, and at several annealing temperatures.

3. SYSTEM CONSIDERATIONS AND TECHNOLOGY DEMONSTRATIONS

A separate paper in this Proceedings as well as a journal article² by Orth et al. describe the results of a system study of the DPSSL driver in a power plant setting. We have found that the DPSSL can be configured and operated within a realistic parameter regime (i.e. the temperature, dimensions, fracture limits, light fluence levels, etc., are all acceptable).

The schematic of a single beamline of our proposed DPSSL driver is sketched in Fig. 5. The architecture bears many similarities with the Beamlet laser at LLNL,¹¹ in that a four-pass amplifier is employed and the pulse is injected near the spatial filter. The Yb:S-FAP gain medium slabs are located at each end of the cavity, and are longitudinally pumped through the end mirrors by the laser diode arrays. The Pockels cell-polarizer pair ejects the $1.047\ \mu\text{m}$ pulse which is then frequency-converted (tripled to $0.35\ \mu\text{m}$) before passing through the heated fused silica final optic wedge (or deflection grating) and impinging on the target. A total of 345 beamlines are needed to deliver 3.7 MJ on-target. The overall efficiency of the laser is calculated to be 8.6% when the cost-of-electricity (COE) is minimized at 8.6¢/kW-hr in the power plant. We note in passing that the laser could operate at 15% efficiency by using more laser diodes and a shorter pump pulse, although this would produce an increase in the COE.

Fig. 5. Schematic of a single DPSSL beamline for IFE. Various physical characteristics are noted from our point design.

We have assembled a small subscale version of the IFE-DPSSL to validate our technologies and predictions to some extent. To accomplish this, we have fabricated a 3 kW laser array operating at the $0.90\ \mu\text{m}$ pump wavelength, and have demonstrated the anticipated gain and efficiency at the $1.047\ \mu\text{m}$ wavelength. Further details concerning these experiments are contained in one of the articles by Marshall et al. in this Proceedings.

4. SUMMARY

We believe that the question posed by the title of this paper can be answered affirmatively. We have developed a solid state laser option suitable for IFE, based on several enhancements over the flashlamp-pumped lasers now deployed for ICF studies, including laser diode pump sources, Yb:S-FAP gain medium, gas-cooled slab thermal management, and heated fused silica final optics. Four other papers in this Proceedings offer additional information concerning this work. An artist's rendition of the power plant follows in Fig. 6.

Fig. 6. Artist's rendition of a power plant based on a DPSSL driver.

5. ACKNOWLEDGMENTS

Many LLNL staff have helped formulate the DPSSL driver concept for IFE, several of which are authors on the other IFE articles present in this Proceedings or as authors on the referenced work. We are particularly grateful to E. M. Campbell for supporting these studies. This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48.

6. REFERENCES

1. Energy and Technology Review, "The National Ignition Facility," December 1994, UCRL-52000-94-12, Distribution Category UC-700 available from National Information Technical Service, U.S. Dept. of Commerce.
2. C. D. Orth, S. A. Payne, and W. F. Krupke, "A diode-pumped solid-state laser driver for inertial fusion energy," UCRL-JC-116173, accepted for publication by Nuclear Fusion.
3. S. A. Payne, W. F. Krupke, L. D. DeLoach, L. K. Smith, W. L. Kway, and J. B. Tassano, "Gain medium for laser-driven inertial fusion energy," Inertial Confinement Fusion Quarterly Report, Vol. 2, No. 2, pp. 51-59, UCRL-LR-105821-92-2, available from National Technical Information Service, U.S. Dept. of Commerce.
4. L. D. DeLoach, S. A. Payne, L. L. Chase, L. K. Smith, W. L. Kway, and W. F. Krupke, "Evaluation of absorption and emission properties of Yb-doped crystals for laser applications," IEEE J. Quantum Electron. 29, 1179-1191 (1993).

5. L. D. DeLoach, S. A. Payne, L. K. Smith, W. L. Kway, and W. F. Krupke, "Laser and spectroscopic properties of $\text{Sr}_5(\text{PO}_4)_3\text{F}:\text{Yb}$," J. Opt. Soc. Am. B 11, 269-296 (1994).
6. S. A. Payne, L. D. DeLoach, L. K. Smith, W. L. Kway, J. B. Tassano, W. F. Krupke, B. H. T. Chai, and G. Loutts, "Ytterbium-doped apatite-structure crystals: A new class of laser materials," J. Appl. Phys. 76, 497-503 (1994).
7. S. B. Sutton and G. F. Albrecht, "Optimum performance considerations for a large-aperture average power solid-state laser amplifier," J. Appl. Phys. 69, 1183-1191 (1991).
8. J. L. Emmett, W. F. Krupke, and W. R. Sooy, "The potential of high-average-power solid state lasers," September 1984, UCRL-53571, available from National Technical Information Service, U.S. Dept. of Commerce.
9. G. F. Albrecht, S. B. Sutton, H. F. Robey, and B. L. Freitas, "Flow, heat transfer, and wavefront distortion in a gas cooled disk amplifier," SPIE 140, 37-54 (1989).
10. J. G. Woodworth, L. L. Chase, M. W. Guinan, W. F. Krupke, and W. R. Sooy, "Final optics for laser-driven inertial fusion target chambers," 14th IEEE/NPSS Symposium on Fusion Engineering (San Diego, CA, Sept. 30-Oct. 3, 1991), 2, 895 (1992).
11. Inertial Confinement Fusion Quarterly Report, Vol. 5, No. 1, pp. 1-85 (1994), special issue on "Beamlet laser project."