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Optimized Flashlamp Pumping of Disk Amplifiers

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Abstract

Disk amplifier design for inertial fusion lasers has evolved with changing fusion-driver requirements from a primary emphasis on gain to a primary emphasis on efficiency. In this paper we compare Shiva and Nova amplifiers to a developmental amplifier (SSA) and show greater than a two-fold improvement in efficiency over past designs under all operating conditions. Experiments to optimize the efficiency of the SSA show that preionization of the flashlamps produces significant benefits and that the packing fraction of lamps is more important than the flashlamp reflector shape. They also show that the optimized flashlamp pulselength and reflector geometry depend on the desired stored energy in the laser medium. We have demonstrated a 7% storage efficiency at a stored fluence per disk of 0.5 J/cm^2 (stored energy density of 0.06 J/cm^3) and 4% at 2.0 J/cm^2 (0.25 J/cm^3). Comparison of SSA measurements with storage-efficiency calculations show that our flashlamp model accurately predicts the single-pass pumping of disk amplifiers.

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Introduction

Disk amplifiers for high-peak-power applications were invented¹ and developed² in the late 1960's and early 1970's to avoid the gain-uniformity problem encountered in scaling rod amplifiers to large apertures. Rod amplifiers are pumped through their cylindrical surfaces, at right angles to the direction of beam propagation as shown in Fig. 1. Absorption of pump power by the laser ions causes a decrease in pumping power with distance into the rod. This tends to create gradients in gain, which cause the output intensity of the beam produced by the amplifier to vary across the beam aperture. Focusing flashlamp reflectors together with the natural focusing action of the radial pumping geometry can be used to compensate for this problem,³ but only for a limited range of ion doping-diameter products. Scaling to larger rod diameters therefore forces a decrease in doping density as it becomes more and more difficult to pump the central region of the rod. Rod amplifiers⁴ have been scaled to clear apertures as large as 12 cm.⁵

Disk amplifiers are pumped through one or both of the disk faces, largely eliminating this problem. As shown in Fig. 1, the gain gradient is perpendicular to these faces and all regions of the laser beam sample the entire gradient. A uniform pump power distribution at the disk surfaces therefore gives a uniform total gain over the disk aperture. Here the doping has no influence on uniformity, and it can be optimized for maximum efficiency. Disk amplifiers become more practical than rod amplifiers at apertures between 5 and 10 cm.

This paper first summarizes the evolution of disk amplifiers at Lawrence Livermore National Laboratory (LLNL), which were developed specifically for use in short-pulse, high-energy lasers to drive inertial fusion reactions. We have concentrated on the face-pumped configuration⁶ shown schematically in Fig. 1, with the disks oriented at Brewster's angle to the beam direction. We will not discuss other successful disk amplifier configurations, such as the "active" mirror amplifier,⁷ also developed for inertial fusion driver applications, or variations of the face-pumped configuration⁸ and the zig-zag slab amplifier,⁹ developed for high-average-power applications.

We next discuss our gain measurement facility, its accuracy and repeatability, and the three quantities necessary to characterize completely the relative performance of different disk amplifiers. The third section introduces two issues generic to disk amplifiers - the need for edge claddings and the asymmetry created in the gain profiles by end effects. We then compare the performance of the five Nova disk amplifiers to an experimental amplifier called the single-segment amplifier (SSA). The following two sections describe the experimental optimization of flashlamp and drive circuits for the SSA and of its reflector geometry. The last section compares SSA measurements with calculations based on a flashlamp model discussed in the previous paper.¹⁰ These results show that we have developed an accurate model for one-pass pumping. However, we have not yet developed a model which adequately treats amplifiers pumped from both sides.

Evolution of Amplifier Design

A series of inertial fusion lasers has been constructed at LLNL with increasing aperture and peak power.¹¹ The design of amplifiers for these lasers has changed, driven by the change in laser pulselength required for larger fusion drivers. From the Shiva laser through Nova, our current inertial fusion driver, to the concepts for a future multi-megajoule laser (MMJ), the laser pulselength desired for target irradiation experiments has increased by two orders of magnitude, from 0.1 to 10 ns. This has reversed the relative importance of amplifier gain and amplifier efficiency.

In all cases we have attempted to minimize the system costs at a given output, as constrained by optical damage and nonlinear self-focusing, the so-called ΔB -limit.¹² However, the 0.1 ns pulselength of Shiva was sufficiently short that the ΔB -limit was reached at peak powers corresponding to average energy fluences well below the saturation fluence of the laser glass. Consequently Shiva amplifiers were designed for maximum gain in order to minimize the beam pathlength in glass and thus minimize ΔB , with little regard for energy-storage efficiency. For Nova, with pulselengths around 1.0 ns, the ΔB -limit allows output fluences which are comparable to the saturation fluence, so that the importance of energy storage efficiency increased relative to gain. The pulselength for a MMJ facility would be around 10 ns, allowing operation into the heavily saturated regime, and

causing storage efficiency to become more important still. Current efforts to improve amplifier performance have therefore focused on improving the energy-storage efficiency of large-aperture disk amplifiers.

The change in amplifier design from Shiva through Nova to proposed MMJ concepts shows the increased emphasis on storage efficiency. Shiva amplifiers, with their emphasis almost entirely on gain, used a cylindrical array of flashlamps which completely surrounded alternating, elliptical disks oriented at Brewster's angle. Figure 2 shows a 9.4-cm Shiva disk amplifier with one of its half-shells of flashlamps removed, showing the orientation of its six disks and the cylindrical flashlamp configuration. For the larger Nova amplifiers (the smaller Nova amplifiers were salvaged from Shiva), the increased emphasis on efficiency resulted in two planar arrays of flashlamps, as shown in Fig. 3 for the Nova 46-cm amplifier. The two flashlamp panels are oriented opposite the disk faces and the top and bottom of the pump cavity consist of flat silvered reflectors. Although slightly higher pumping powers were possible with the Shiva design, omission of those flashlamps looking primarily at the edges of the disks significantly improved amplifier efficiency.¹³

We have continued this trend toward improved efficiency in our current developmental amplifier^{14,15} shown in Fig. 4. This amplifier was designed to simulate one segment of a very large array of amplifiers, and is therefore called the single segment amplifier (SSA). Its geometry differs from the Nova amplifiers primarily in its use of rectangular disks. Eliminating the gaps around the elliptical disks forces all pump light to pass through a disk before reaching the opposite flashlamp

panel. Because flashlamps absorb as well as emit pumplight, it is desirable that the pump emission pass at least once through a laser disk before encountering a flashlamp. The rectangular shape substantially increases disk area relative to reflector and lamp surface area tending to promote absorption by the laser disk.

One of the goals of our SSA development program is to test the pumping configuration envisioned for the amplifiers of a MMJ facility. A concept for a MMJ output stage amplifier is a compact, multi-segment amplifier,¹⁶ as shown in Fig. 5. Segmentation of the disks is required to reduce the loss rate to amplified spontaneous emission (ASE)¹⁷ and is employed in the 46-cm amplifiers of Nova. Figure 5 shows a multi-segment amplifier with six disks per beamline and with a five-by-five segmented aperture, forming 25 independent beamlines. Planes of flashlamps along the vertical segmentations in the interior of the amplifier have reflectors between them which divide the light evenly to pump disks on both sides. Flashlamps along the exterior walls, packed at one-half the density as those on the interior, have conventional reflectors which direct the light inward. Figure 5 shows one group of five amplifier segments horizontally displaced from the others to indicate the proposed cellular nature of the assembly.

The amplifier development program at LLNL complements the open flashlamp work discussed in the previous paper.¹⁰ The open-flashlamp studies have attempted to understand the electrical-to-optical transfer efficiency of flashlamps while the SSA studies have attempted to understand the flashlamp-to-disk transfer efficiency. Together they are aimed at providing the basic understanding required to develop an accurate model for the flashlamp pumping of disk amplifiers.

Experimental Technique

We determined amplifier performance by measuring gain as a function of time using a cw Nd:YAG probe laser. We calculated stored energy and hence storage efficiency from the measured peak gains, using the published value for the stimulated emission cross section of the laser glass.¹⁸ We have emphasized measurement accuracy and repeatability.

Figure 6 shows a schematic of the setup used for gain measurements. An etalon internal to the Nd:YAG resonator allowed operation on the Nd:YAG transition closest to line center of the amplifier being tested. We monitored the probe laser power before transmission through the amplifier (reference signal) as well as after (amplified signal) to account for fluctuations in power. Diffraction gratings and color filters in the reference and amplified signal arms provided spectral discrimination against flashlamp light. Combined spectral and spatial filtering in both arms reduced flashlamp light to less than 0.1% of the probe signals. A TV camera was imaged on the spatial-filter pinhole in the amplified signal arm, the position with the tightest alignment tolerance, to give a continuous confirmation of alignment.

The reference and amplified probe signals were digitized and processed by computer to increase our measurement precision. We divided the amplified and reference waveforms, normalized the ratio, and smoothed¹⁹ around its peak in time to find the maximum gain. Figure 7 shows typical waveforms from a relatively low-gain shot. The raw transmitted signal is shown in (a), after dividing out the reference in (b), and after smoothing in (c).

Figure 8 shows standard deviations for peak amplifier gain plotted as a function of gain, statistically determined from several data sets taken on a standard configuration of the SSA. We typically did not take enough data to determine errors statistically for each data run. Instead, we estimated the error for each data point from the curve shown in Fig. 8 and divided by the square-root of the number of shots for that data point. Figure 8 also shows that the standard deviation remains finite as the gain approaches unity, presumably because of digitizing errors. Consequently, multi-passing the probe beam through the amplifier for low-gain configurations to increase the measured gain signal generally improved accuracy. We periodically repeated gain measurements on a standard configuration of the SSA to test for aging effects. Gain coefficients repeated to within error bars for the lower values of gain and to within $\pm 1\%$ otherwise after more than 2500 shots over a 12-month period.

We measured the peak amplifier gain G in time and calculated the peak gain coefficient g and the total stored energy E_s from the relations:

$$g = \ln G / [mt(1 + 1/n^2)^{1/2}] \quad (1)$$

$$E_s = gh\nu C_s V / \sigma_m \quad (2)$$

for an amplifier with m disks of thickness t and refractive index n , mounted at Brewster's angle, and where

- h = Planck's constant,
 ν = frequency at peak gain,
 C_s = spatial-uniformity correction factor to account for the difference between the measured gain coefficient and the average gain coefficient over the full clear aperture of the amplifier,
 V = total volume of laser glass in the amplifier accessible to a laser beam, and
 σ_m = gain cross section of the laser glass at the measurement wavelength.

Table 1: Physical parameters of the Nova amplifiers and the SSA

Amplifier	Clear aperture (cm)	Number of disks	Disk thickness (cm)	Glass volume/disk (l)	Nominal pulselength $3\sqrt{LC}$ (μs)
Shiva/Nova	9.4	6	2.5	0.36	660
Shiva/Nova	15	4	3.0	1.06	660
Nova	20.8	3	3.0	1.96	660
Nova	31.5	2	4.3	6.5	920
Nova	46	2 pairs	4.3	13.6/pair	800
SSA	32	4	4.3	8.7	660

The Nova amplifiers use a phosphate laser glass, either LHG-8 (Hoya) or LG-750 (Schott) with an index of 1.52, and a cross section at line center of $4.0 \times 10^{-20} \text{ cm}^2$.¹⁸ For these measurements on the SSA we used a silicate glass, LG-660 (Schott) with an index of 1.52, and a peak cross section of $1.93 \times 10^{-20} \text{ cm}^2$.¹⁸ To determine σ_m we assumed that σ scales as $\lambda^5 I(\lambda)$, where $I(\lambda)$ is the measured fluorescence line shape.¹⁸ Disk dimensions required to evaluate Eq. 1 and 2 are found in Table 1.

Three quantities are required to specify amplifier performance: gain, stored energy, and storage efficiency. Two of these, gain and stored energy, are not immediately useful for comparing different disk amplifiers, because of the different numbers of disks and the range in aperture sizes of disk amplifiers. Since the number of disks in a given amplifier is quite arbitrary, ranging from 2 to 6 in the Nova amplifiers (selected to give a common flashlamp length), the relevant quantity for comparing different amplifiers is gain/disk. Similarly energy/disk is more relevant than total stored energy. However, since the aperture area varies, stored-energy/disk/beam-area is a better general parameter. We call this last quantity the stored-fluence/disk. This is the extractable fluence per disk available to a full aperture beam. For amplifiers with the same saturation fluence, either efficiency and gain/disk or efficiency and stored fluence/disk completely characterize performance.

Efficiency versus stored energy density E_s/V is commonly used in comparing amplifier performance, but it is inappropriate for comparing amplifiers with different disk thicknesses. Thinner disks produce a higher storage density than thicker disks, under identical pumping conditions, even though thicker disks have a higher stored fluence.

Hence, comparing efficiency as a function of storage density can give a false impression of performance if the disk thicknesses are different. We prefer to compare efficiency as a function of stored-fluence/disk or, when the disk thicknesses are the same, as a function of stored energy density.

Generic Disk Amplifier Issues

There are two aspects of disk amplifiers which require specific mention, edge claddings and gain uniformity. Disk amplifiers require edge claddings to suppress parasitics and to minimize the loss rate to ASE.¹⁷ Most of the spontaneously emitted photons within a disk are trapped by total-internal-reflection at the surfaces and experience relatively long and loss-free gain paths to the disk edges as indicated in Fig. 9. In the worst case, parasitic oscillation occurs when the edge-to-edge gain exceeds the reflection loss at the disk edge. Even below threshold, the regeneration caused by partially-reflecting edges can significantly increase the loss rate from ASE. The purpose of the edge cladding is to provide absorption at the disk edge to keep parasitic oscillations well below threshold. Nonetheless, single-pass ASE can substantially increase the inversion decay rate for large products of gain coefficient times disk dimension.

We developed a polymer-based edge cladding²⁰ for our SSA studies. The monolithic glass edge claddings²¹ used in the Nova amplifiers perform extremely well, but are expensive and must be reformulated for each type of laser glass. The new cladding can be applied to a wide variety of laser glasses and promises to be much less expensive. A clear silicone rubber couples ASE from the disk edge to glass absorbing plates

surrounding the disk as shown in Fig. 10. Both the silicone rubber and the absorbing plates were scatter-free and were index matched to the laser glass to prevent reflections. The cladding was formed by filling the spaces between disk and absorber plates with the disk in its disk holder. This edge cladding effectively "pots" the disk into its holder with a thick rubber pad, forming an ideal, stress-free mechanical mount for the disk when mounted on its edge.

Testing in large aperture amplifiers has demonstrated the performance and survivability of the new type of cladding in the harsh environment of the amplifier. Rubber-clad and glass-clad disks performed identically in a Nova 31.5-cm amplifier over the entire operating range of the amplifier. The four originally-clad disks in the SSA have now experienced more than 4000 shots with no measurable degradation of amplifier performance.

The second issue peculiar to disk amplifiers is the slightly asymmetric gain profile due to the loss of pump light directly out the ends of the amplifier. Figure 11 shows both a schematic view of the two-disk, 31.5-cm Nova amplifier as seen from above, and the variation of its gain coefficient along horizontal and vertical centerlines. The schematic diagram illustrates that the upper plane of flashlamps radiates some of its pump light directly out the ends, whereas all of the pump light from the lower plane is directed at the disks. As a result the outer faces of the disks near the amplifier ends, marked "L", receive less pump light than those further into the amplifier, marked "H". The tilt of the horizontal gain profile in Fig. 11 results from this variation

in pumping. The gain fall-off near the top and bottom of the amplifier results from a partial shielding by the disk holder of pump light reflected off the top and bottom reflectors.

All disk amplifiers of this type with even numbers of disks exhibit this type of gain asymmetry. We use this asymmetry to distinguish horizontal directions in the amplifier by defining the high and low gain sides as the "+" and "-" horizontal directions, respectively. The total variation decreases with increasing numbers of disks in the amplifier, simply because the end effect becomes a smaller part of the total. For amplifiers with an odd number of disks, the high and low sides alternate at the two ends, and the asymmetry tends to cancel. For example, the horizontal profile for the three-disk, 20.8-cm Nova amplifier is flat to within $\pm 1\%$, compared to the 20% change shown in Fig. 11 for the two-disk, 31.5-cm amplifier. Gain asymmetry in systems with more than one amplifier per stage can be substantially reduced by alternating the high and low gain sides of adjacent amplifiers.

Performance Comparison of the Nova Amplifiers and the SSA

Figure 12 shows efficiency as a function of stored-fluence/disk (J/cm^2) for the five Nova amplifiers. Efficiency is defined here as the stored energy in the laser glass divided by the initial bank energy. The larger data points indicate typical operating points. These amplifiers all had the same type of phosphate laser glass (Schott LG-750 or Hoya LHG-8). Table 1 gives some of the physical parameters of the Nova amplifiers and of the SSA, and it shows the flashlamp pulsewidths used to obtain these results.

Figure 12 shows that storage efficiency in the Nova amplifiers increases fairly consistently with aperture. This trend is caused by a change in the pump configuration (from cylinder to box) as well as a monotonic increase in the area that the laser disk represents compared to other absorbers in the cavity. The three larger amplifiers with two-sided pumping geometries have 1.5 to 3 times higher efficiencies than the 9.4-cm and 15-cm amplifiers with cylindrical pumping geometries. On the other hand, the smaller amplifiers reach the highest gains and stored fluences, consistent with their design emphasis. Table 1 shows there are significant differences in disk thickness and flashlamp pulsedwidth among the amplifiers, which also influence performance. The flashlamp-packing-fraction varies among them and, as we will show, this influences efficiency as well.

Figure 13 shows the efficiency of the rectangular-disk SSA and the two largest Nova amplifiers, compared as a function of both stored-energy-density and stored-fluence/disk. Stored-energy-density is appropriate in this case, because the amplifiers all utilize the same thickness disks. We configured the amplifier as similarly as possible for these measurements. We used blast shields between flashlamps and disks (to isolate the disk region acoustically from the flashlamps), we used bead-blasted aluminum end plates, and we selected a flashlamp pulselength for the SSA comparable to that of the Nova amplifiers. Figure 13 shows that in this so-called "standard configuration", the SSA gives about twice the storage efficiency of the best Nova amplifier.

The improved efficiency of the SSA results from several factors besides the use of rectangular disks. The SSA disks were doped more heavily than the Nova disks, 4×10^{20} Nd ions/cm³ compared to 2×10^{20} ions/cm³. The SSA used a lower gain cross-section glass, which gave a lower loss rate from ASE. End effects for the SSA are less, because it has four disks compared to only two for the 46-cm and 31.5-cm amplifiers. Also the silver-reflecting surfaces in the SSA had somewhat higher reflectivity than those of the Nova amplifiers. Nevertheless, we estimate that these factors still leave a 25% to 50% improvement attributable to the rectangular-disk pumping geometry.

SSA Drive Circuit and Flashlamp Optimization

To optimize the flashlamps and drive circuits we varied the type of gas fill in the flashlamps, their fill pressure, and the input pulsewidth. In addition we operated the lamps with and without a preionization pulse to precondition the lamps for the main discharge. Figure 14 shows the circuit used to drive the SSA flashlamps (and the Nova amplifiers). The SSA used 1.5 cm bore, cerium-doped-quartz flashlamps with 234-cm arc lengths. Most of the SSA data were taken with xenon lamps, factory-filled to a pressure of 300 Torr, but refillable lamps were used for the data described in this section. Comparison tests between the factory and lab-filled lamps gave identical performance within error bars.

Each flashlamp had its own capacitor and inductor connected in parallel, with up to a total of 16 circuits across the common ignitron switch. The resistance R (in Fig. 14) represents the total resistance per circuit from cables, inductor, and the main bank ignitron switch. For initial bank voltages higher than about 12 kV, closure of the switch S gave enough voltage at the lamps to break the lamps down and initiate the main discharge. For lower initial bank voltages the preionization circuit, consisting of the small capacitor C_p and an additional ignitron switch S_p in parallel with the main switch, supplied a low-energy, high-voltage pulse to break down the lamps before the main bank was switched. The operation of this circuit with preionization is described in the previous paper.¹⁰

We attempted to maintain comparable electrical conditions for the comparison of SSA performance with different flashlamp pulselengths and with different gases and fill pressures. This required control of the flashlamp explosion fraction f_x and the circuit damping parameter α .²² Explosion fraction is defined as the ratio of the total energy supplied to a lamp to the single shot explosion energy of the lamp E_x , and is therefore proportional to the total energy into the lamp. The shape of the power pulse applied to the lamp depends primarily on the circuit damping parameter α . These parameters are defined as:

$$f_x = \frac{1}{2} CV^2 / E_x \quad (3)$$

$$E_x = (20,000) \text{ } \& \text{d (LC)}^{1/4} \quad (4)$$

$$\alpha = \frac{K_0}{\sqrt{V_0 Z_0}} \quad (5)$$

where the lamp impedance parameter K_0 is given by

$$K_0 = 1.3(\ell/d)(P/450)^{0.2} \quad (6)$$

The circuit capacitance and inductance are C and L (in μF and μH , respectively); the initial bank voltage is V (in volts); the explosion energy is in joules; the bank impedance Z_0 is $\sqrt{L/C}$; flashlamp arc length is ℓ and bore size is d (both in cm), and flashlamp fill pressure is P (in Torr). We compared SSA performance for different flashlamp pulselengths and fill pressures attempting to select the circuit parameters L, C, and V to keep α constant at the same f_x . One can show from Eq. 3, 4, and 5 that matching α at constant f_x for circuits which deliver different pulselengths $3T$ (where $T = \sqrt{LC}$), requires that C, L, and V vary as $T^{5/6}$, $T^{7/6}$, and $T^{-1/6}$, respectively.

We found that the changes required to optimize the lamp and drive circuit also required a change in our definition of storage efficiency. Changing the gas type or fill pressure in the lamps, circuit parameters, or the number of circuits fired, caused small changes in the total transfer efficiency of electrical energy from the bank to the flashlamps. To remove this effect, which obscures the performance differences we were interested in, we redefined storage efficiency as the ratio of stored energy in the laser glass to the energy delivered to the lamps, including preionization energy.

There were no surprises when we optimized gas type and fill pressure. Xenon outperformed krypton and argon over the range of operating conditions tested. Varying the fill pressure of xenon gave very flat maxima in efficiency between 150 and 300 Torr, independent of $3T$ and f_x . The maxima dropped less than 2% for two-fold changes in pressure about the maxima. Both of these results agree with open-flashlamp measurements.

We found that preionization improved performance under all operating conditions, but most markedly for short pulselengths and relatively low input energies. Figure 15 shows storage efficiency versus f_x for three values of pulselength, each with preionization (solid line) and without preionization (dashed line). We could not obtain data without preionization at f_x values less than about 0.06, because the corresponding initial bank voltages were insufficient to trigger the lamps. Without preionization, the efficiency curves maximize for a 3T value of about 290 μ s, but with preionization the peak efficiency continues to increase for shorter pulselengths.

Figure 15 also shows that preionization causes a slight reduction in the transfer efficiency to the lamps. The data points with preionization are all shifted slightly to the left compared to those without for the same initial conditions, indicating a slightly lower delivered energy. This presumably occurs because preionization reduces the impedance of the lamp.

The effect of shorter pulselengths on SSA performance is illustrated in Fig. 16 which shows efficiency versus stored energy density for six pulselengths. We characterize the radiative lifetime of the SSA disks by the first e-folding time of the laser glass, since LG-660 glass does not give a single exponential radiative decay. The average of the first e-folding times for the 5x5x0.5 cm³ witness samples made with the SSA disks is 350 μ s. The six values of pulselength shown in Fig. 16 therefore represent pulselength-to-lifetime ratios ranging from 0.5 to 2.7.

Figure 16 shows that changing the flashlamp input pulselength greatly improves storage efficiency at low values of stored energy density, but that the optimum pulselength depends on the desired operating point for the amplifier. A maximum performance envelope is defined with different pulselengths for different values of stored energy density. Each of these curves is terminated at the high stored-energy-density end by the maximum safe voltage we could use with existing circuit components.

Pumping Configuration Optimization

We tested the seven reflector geometries shown in Fig. 17. The acronyms indicated in the figure consist of the number of lamps per side and a letter indicating the shape, C, F, and R for cylindrical, flat, or Rabl. All reflectors were silver-coated, some by electro-plating and some by vacuum deposition with overcoatings of either MgF_2 or SiO_2 . We have been unable to obtain spatially-averaged reflectivities in some cases because of the short and/or changing radii-of-curvature. However, only one of the conclusions of this section would be affected by the relatively minor reflectivity differences.

For the reflectors shown in Fig. 17, the flashlamp packing fraction as well as the shape is varied. Lamp packing fraction is defined as the projected area of the lamps divided by the total area of the output plane of the flashlamp panel. Our definition of projected lamp area is based on the bore diameter of the flashlamps. Thus, the flashlamp packing fractions were 0.14, 0.19, 0.23 and 0.38 for the 3, 4, 5, and 8-lamp

reflectors, respectively. Lamp packing fraction and reflector shape are not entirely independent, since a specific shape cannot always be preserved for a change in lamp packing fraction. However, these two variables affect different aspects of the pumping, and therefore might be expected to optimize differently.

Lamp packing fraction determines the total pumping power inside the amplifier. Larger lamp packing can give higher gains and stored fluences. However, a simple physical argument suggests that an optimum packing fraction exists when efficiency is considered, even for the highest possible gains and stored fluences. If we assume that the flashlamps are true blackbody radiators which emit into 2π steradians from the inner surfaces of their quartz envelopes, then the power density at the output plane of the reflector cannot exceed that at their inner surface, by conservation of brightness ($\text{watts/cm}^2/\text{sr}$).²³ As lamp packing fraction increases, the pumping power density at the output plane can increase only to that value at the radiating surface, since the angular distribution there is also limited to 2π steradians. Further increases in lamp packing fraction can only result in more light going directly back into the lamp from which it was emitted without passing through a laser disk, what we call direct feedback. Direct feedback to blackbody-like lamps would be absorbed, presumably raising their temperature and total output power, but nonetheless leading to a net loss of efficiency. The lamp packing fraction which matches the area of the inner cylindrical surface of the lamp to the area of the output plane of the reflector, a lamp packing fraction of $1/\pi$, therefore gives the

maximum pumping power without necessarily increasing direct feedback. Since we know the flashlamps are somewhat "gray" rather than black, the optimum lamp packing fraction of $1/\pi$ is only approximate.

The shape of a reflector determines the degree of direct feedback to the lamps and the angular distribution of light in its output plane. The angular distribution of light influences the average number of reflections required to reach the disks, and it influences the amount of Fresnel reflection at the disk surfaces. If the number of reflections from lamps to disks were the same, we would expect a smaller angular distribution to produce higher efficiency.

The seven reflector geometries gave variations in lamp packing fraction, direct feedback, and output angular distributions. The Rabl-shaped reflectors²⁴ have the property that none of the light emitted from the lamp can go directly back into that lamp, thus eliminating direct feedback. Also, for the "deep" Rabl-reflectors the width of the angular distributions transverse to the lamp axes becomes relatively small, going from $\pm 80^\circ$ to $\pm 45^\circ$ to $\pm 30^\circ$ for the 5R, 4R, and 3R reflectors, respectively. For the cylindrical reflectors the amount of direct feedback increases with lamp packing fraction but is always less than a flat reflector with the same packing fraction.

Figure 18 shows the SSA efficiency versus explosion fraction for the seven reflector geometries. This presentation compares performance at the same lamp conditions, and thus shows only differences in the lamp-to-disk transfer efficiency. It hides the considerable differences in stored energy at a given f_x . These data were taken with the SSA configured without blastshields, with black ends, and with a flashlamp

pulselength of 660 μ s. The data have been corrected slightly to remove the effects of ASE based on measurements of the type described in reference 15. We found that ASE for these conditions produces a linear reduction in efficiency with peak stored energy density, amounting to an 11% decrease at 0.20 J/cm³.

The curves in Fig. 18 have similar shape except that they generally fall off more rapidly with lamp input as the packing fraction increases, causing the peak efficiency to move toward lower explosion fractions. This effect is most obvious for the 8C reflector. It results from the general increase in direct feedback with lamp packing fraction and the increase in flashlamp absorption with loading (for example, see ref. 10).

A conspicuous conclusion from Fig. 18 is that the smaller lamp packing fractions generally give higher efficiencies and therefore higher lamp-to-disk transfer efficiencies. This is surprising considering the substantial differences in reflector shape, but only the ordering of 3C below 4R does not support it. The three cylindrical cases demonstrate it most clearly, but it is also true for the Rabl reflectors. A related conclusion is that shape is less important than lamp packing fraction, since the spread in performance among the three shapes with 5 lamps and the two shapes with 3 lamps is less than the total spread between them. The 3-lamp and 5-lamp cases also show that the Rabl shape is the best, although the difference between 5R and 5C performance is of little consequence.

The three Rabl cases have no direct feedback so that the primary difference among them is a continuously decreasing and more disk-directed angular distribution going from the 5R to the 3R case. However this is

the one example where reflectivity differences influence our conclusions. Although the 3R and 4R cases appear to perform 10% better than the 5R case, a sizeable fraction of this difference is attributable to reflectivity differences.

Figure 19 shows the same data as Fig. 18, but without the ASE correction and with storage efficiency plotted against stored energy density. This presentation shows the total amplifier performance for each pumping configuration, and it substantially shifts the relative positions of the curves. The lower lamp packing fractions reach higher efficiencies only at low stored energies, because their efficiencies decrease as the lamps are loaded more heavily. Higher stored energies require more lamps in order to avoid driving the lamps too hard. Now it can be seen that the 4R case performs the best over its entire operating range, although the difference between the 4R and 5R cases at the maximum stored energy density can be attributed to reflectivity differences. It is now also apparent that the best lamp packing fraction depends on the desired operating point of the amplifier. For stored energy densities below 0.24 J/cm^3 the 4R case gives the best performance. Above that the 5R would be best, and possibly even a 6-lamp configuration would win near 0.30 J/cm^3 . It is clear that 8-lamps per side is too many. The optimum lamp packing fraction for maximum stored energy density appears to be between 0.23 and 0.38, in reasonable agreement with the estimate of $1/\pi$ based on the assumption of blackbody behavior.

Gain uniformity became a serious issue for those reflector geometries in Fig. 17 with less than 5 lamps per side. Gain measurements at several different aperture positions showed spatially oscillating gain

profiles for pumping configurations with only three and four lamps per side. The solid curves in Fig. 20 show gain scans in the horizontal direction for the 5R, 4R, 3R, and 3C cases. (The horizontal direction is the plane of the paper for the schematic amplifier in Fig. 11). We also measured gains in the vertical direction at five horizontal positions; the averages of the vertical scans are shown by the dashed curves. Departures of the solid curves from the dashed curves indicate spatial oscillations in the vertical direction. Oscillation amplitudes were as large as $\pm 15\%$ for the 3R case, and their presence greatly increased the amount of spatial gain data needed to determine the spatial uniformity correction C_s used in Eq. 2. Notice that the dashed curves showing the vertically-averaged horizontal profiles all have similar slopes. In fact, all seven pumping configurations give similar slopes. Since loss of pump light out of the ends of the amplifier causes this slope, it follows that end loss for all these pumping configurations is about the same.

Comparisons with Calculations

The simplest case to model is that of pumping the amplifier from only one side. This avoids the complication of multiple passes of pump light through disks and the absorption and reemission of light by flashlamps on the opposite side of the amplifier. To measure single-pass storage efficiencies, we used blackened panels on both ends of the SSA and on the side opposite the flashlamps to absorb all flashlamp light after a single pass through the disks. We installed the lamps on the "-"

side of the amplifier, as defined in Fig. 11, to avoid the loss of pump light directly out the ends of the amplifier. We used Rabl-shaped flashlamp reflectors without blast shields to minimize direct feedback to the flashlamps, although Fresnel reflection at the disk surfaces inevitably provided some feedback. Finally, we used the 3R reflector for the comparison because it gave the highest measured single-pass pumping efficiencies, implying the highest transport efficiency from flashlamp to disks. Figure 21 shows storage efficiency versus lamp input for single-pass pumping with this 3R configuration. The data has had the effect of ASE removed, as described with regard to Fig. 18.

The calculation of single-pass pumping efficiencies was done with a model based on the open flashlamp measurements described in the previous paper.¹⁰ The experimentally measured power into the flashlamps as a function of time was taken as input to the model. This allowed prediction of the output power and hence the instantaneous pumping rate. A rate equation for the population inversion in the disks, which included a 3-term exponential fit to the measured spontaneous decay rate of LG-660 glass, was then solved to calculate the peak stored energy, assuming the transport efficiency of pump light to the disks was unity.

Figure 22 shows the ratio of the measured efficiencies in Fig. 21 to calculated efficiencies as a function of lamp input. The error bars reflect the uncertainty in the measured efficiencies, and the solid curve is a least-squares fit to the data points including the error bars.

There are two aspects of Fig. 22 worthy of note, the flatness of the curve with change in lamp loading f_x , and its value of approximately 0.75. Although the model over estimates efficiencies somewhat at low

f_x , the overall flatness confirms that the variation in lamp spectra with input, the so-called blue shift of the lamps, is well treated by the flashlamp model. The 0.75 value of the ratio provides an estimate of the lamp-to-disk transport efficiency, since the calculation assumes no loss of pumping power from lamp to disk. An accurate calculation of just the lamp-to-disk transport efficiency requires a 3-D ray tracing code and has not yet been done. However, we can estimate the effect of the two primary sources of loss, finite reflectivity and the fact that the disk holders block some of the pump light. The spatially averaged reflectivity of the 3R reflector, averaged over the 5 pump bands of Nd^{3+} , is $96 \pm 2\%$, and the average number of bounces taken by light rays in getting to the disk is 1.3, based on 2-D ray-tracing calculations. The transport factor due to finite reflectivity therefore ranges from 0.92 to 0.97 for the most probable range of reflectivities. The blockage of pump light by the disk holders amounts to 4% of the arc length by the disk ends nearest the lamps (this light is likely lost) and another 4% on the opposite side (this may or may not be lost). These contribute a second factor of 0.92 to 0.96. Combining the two gives a range in transport efficiency of 0.85 to 0.93, compared to the 0.75 from the model calculation. Given the fact that we have not attempted to consider the effect of Fresnel-reflected light from the disks or the uncertainties of the calculation itself, we consider this good agreement. This agreement and the flatness of the ratio indicate that our model quantitatively predicts single-pass pumping with good accuracy.

Pumping from both sides of the amplifier introduces competitive effects, the multiple passing of pump light which does not get absorbed on the first pass through the disks and absorption and recycling of that light in the flashlamps. Experimentally we observe that efficiencies

from two-sided pumping rolloff faster with f_x than one-pass pumping. Predictions of two-sided pumping, however, require a good understanding of the recycling of light in flashlamps and a 3-D ray-tracing code to calculate transport efficiencies and to determine where the unused pump light goes. Both are the subjects of on-going work at LLNL.

Conclusions

Changing ICF driver requirements have increased the importance of storage efficiency compared to gain in the design of large disk amplifiers. An experimental program to understand the flashlamp pumping of disk amplifiers and to demonstrate performance improvements has shown that optimization of the drive circuit and reflector geometry depends on the desired operating point of the amplifier. The best measured performances are a 7% storage efficiency at a stored-fluence/disk of 0.5 J/cm^2 (an extractable energy density of 0.06 J/cm^3) and 4% storage efficiency at a stored-fluence/disk of 2.0 J/cm^2 (0.25 J/cm^3). Comparison of amplifier measurements made with one-pass pumping agree well with calculations based on open-flashlamp measurements.

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Figure Captions

1. Schematic illustration contrasting the different pumping configuration of rod and disk amplifiers.
2. A Shiva 9.4-cm amplifier showing the cylindrical flashlamp array which surrounds its elliptical disks.
3. A Nova 46-cm amplifier showing its two-sided pumping configuration and elliptical disks.
4. The developmental amplifier (SSA) with two-sided pumping and rectangular disks to simulate one segment of a large, segmented-aperture amplifier.
5. A compact, multi-segment amplifier concept for a future multi-megajoule laser driver for inertial confinement fusion.
6. A schematic of the gain measurement set-up, showing reference and amplified signal channels.
7. Representative waveforms showing the raw amplified signal, the normalized ratio of amplified and reference signals, and the ratio after smoothing near its peak.
8. Experimentally determined standard deviations in gain for a single configuration of the SSA.
9. Laser disk cross section contrasting the gain path lengths for the beam and amplified spontaneous emission (ASE) to show the need for edge claddings.
10. Cross section of a laser disk and disk holder showing the implementation of a polymer-based edge cladding.

11. Horizontal and vertical gain profiles of a Nova 31.5-cm amplifier showing the typical asymmetry caused by end effects. The schematic in a) shows a top view of the amplifier to distinguish the horizontal and vertical profiles in b).
12. Storage efficiency versus stored fluence/disk for the five Nova amplifiers with their typical operating points indicated by the solid circles.
13. Storage efficiency versus stored energy density and stored fluence/disk for a Nova-like configuration of the SSA and for the two largest Nova amplifiers.
14. Schematic of the flashlamp driving circuits for the SSA, showing connections to high voltage supplies V, energy storage capacitors C, current limiting inductors L, distributed resistance R, and ignitron switches S. The subscript p designates preionization circuit (PILC) components.
15. SSA storage efficiency versus explosion fraction with and without preionization for three flashlamp pulselengths.
16. SSA storage efficiency versus stored energy density for six flashlamp pulselengths.
17. Cross sections of the seven flashlamp reflector geometries with their lamp packing fractions, reflector shapes, and identification acronyms.
18. SSA storage efficiency versus explosion fraction for the reflector geometries of Fig. 17, with ASE effects removed.
19. SSA storage efficiency versus stored energy density for the reflector geometries of Fig. 17.

20. SSA horizontal gain profiles for four reflector geometries showing as-measured profiles (solid) and vertically averaged profiles (dashed).
21. SSA storage efficiency versus explosion fraction for single-pass pumping with the 3R reflector and with ASE effects removed.
22. Ratio of measured to calculated storage efficiencies versus explosion fraction for single-pass pumping of the SSA.

Figure 1

Figure 2

46cm TWO DISK AMPLIFIER

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9

Figure 10

Figure 11

Figure 12

Figure 13

Figure 14

Figure 15

Figure 16

Figure 17

Figure 18

Figure 19

Figure 20

Figure 21

Figure 22