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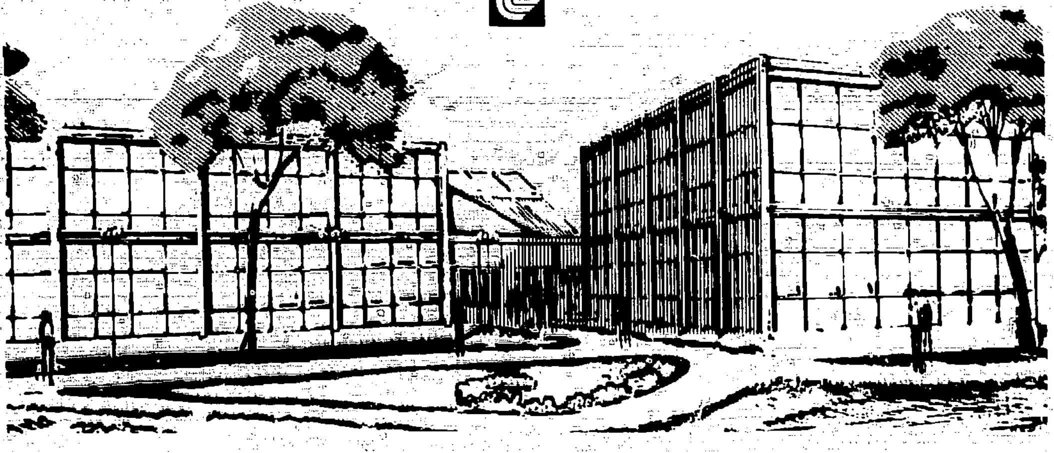

MASTER

LARGE APERTURE COMPONENTS FOR SOLID STATE LASER FUSION SYSTEMS*

by

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ABSTRACT

Solid state lasers for fusion experiments must reliably deliver maximum power to small (approximately .5 mm) targets from stand-off focal distances of 1 m or more. This requirement places stringent limits upon the optical quality, resistance to damage, and overall performance of the several major components -- amplifiers, Faraday isolators, spatial filters -- in each amplifier train. Component development centers about achieving (1) highest functional material figure of merit, (2) best optical quality, and (3) maximum resistance to optical damage. Specific examples of the performance of large aperture components will be presented within the context of the Argus and Shiva laser systems, which are presently operational at Lawrence Livermore Laboratory. Shiva comprises twenty amplifiers, each of 20 cm output clear aperture. Terawatt beams from these amplifiers are focused through two opposed, nested clusters of f/6 lenses onto such targets. Design requirements upon the larger aperture Nova laser components, up to 35 cm in clear aperture, will also be discussed; these pose a significant challenge to the optical industry.

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I. Introduction

Components of large solid state laser systems must meet stringent performance requirements if these lasers are to perform to their fullest potential as fusion target irradiation facilities. Disk amplifiers (up to 34 cm clear aperture) must provide high specific gain and energy storage; lens-pinhole-lens vacuum spatial filters (up to 50 cm clear output aperture) must remove small-scale spatial irregularities from the beam, and in addition provide for image relaying; Faraday isolators (up to 22 cm clear aperture) must protect long chain amplifiers against self-oscillation; Pockels' cells (up to 10 cm clear aperture) must reduce amplified spontaneous emission and prepulse energy at the target to acceptable levels; and large turning mirrors (up to 50 cm clear aperture) must be capable of accurately pointing and centering the beam on the target focusing lens, while permitting "look through" capability for beam and target diagnostics. It is not the intent here to present amplifier, rotator, and Pockels cell design rules and functionality; rather, attention shall be focused upon the importance of component optical specifications to laser performance. These will be discussed within the context of both present (Argus, Shiva) and planned (Nova) systems.(1,2)

Solid state systems intended for high power operation are characteristically limited in performance by three mechanisms:

1) The nonlinear, intensity dependent refractive index n_2 of the components through which the beam passes, which causes self-focusing instabilities and degradation of focusable power.

2) Component damage, particularly to coated optical surfaces, when local beam intensity or fluence exceeds damage thresholds.

3) Linear aberrations, associated with the more than 100 optical components through which the beam passes, cause focal spot blurring.

Each of these mechanisms will be discussed in turn in the paragraphs to follow.

II. Nonlinear Self Focusing

Small irregularities in the beam spatial profile grow exponentially with further propagation through glass components. The rate of growth depends upon the characteristic spatial frequency of the irregularity and the details of component spacing in the chain itself. Swiftest growth of beam modulation occurs exponentially with argument B, a parameter numerically equal to the nonlinear phase retardation of the beam (relative to its phase after passage through the same thickness of a linear refractive index material). In turn, B is proportional to the nonlinear refractive coefficient of the glass, the beam intensity, and the thickness of the components along the optical path. Experiments show(1) that B must be less than (about) 3 between sequential spatial filters in order to avoid catastrophic self-focusing instabilities (this fact has a profound influence upon solid state laser chain architecture). Consequently, in order to realize maximum beam power for a fixed aperture, the number of components, their thickness, and their nonlinear refractive index n_2 must all be minimized. The latter parameter presents the most significant leverage in increasing system performance. This fact has driven the development of new, low n_2 glasses for laser amplifiers.

The disk amplifiers used in Argus and Shiva are made from silicate glass, which remains the most widely used glass in laser amplifiers today. More recently, phosphate glasses, with a lower n_2 than silicates, have been extensively developed and employed in large systems. Fluorophosphate glasses, with still lower n_2, are being developed for use in the large Nova laser facility, which is presently under construction at Lawrence Livermore Laboratory. Table I illustrates material figures of merit for each of these laser amplifier host glasses. Also shown are representative cross-sections for stimulated emission for the 1 μm Nd^{3+} transition for each glass. The characteristic cross-section significantly influences cost-effective laser chain design, with higher cross-sections tending to favor smaller final clear apertures and shorter chains. A full discussion of these design issues is beyond the scope of this paper.

Table I

	Silicates	Phosphates	Fluorophosphates
n^2/n_2 (Disk Amps)	1.0	1.4	2.3
σ (typ.)	$2.7\times10^{-20}cm^2$	$4\times10^{-20}cm^2$	$2.5\times10^{-20}cm^2$

Spatial beam noise can originate from optical imperfections in the components (bubbles, striae, etc.) or on their surfaces. We have identified the major source of small-scale modulation to be small (typically 200 μm) damage sites. These occur most frequently on the surfaces of amplifier disks, where their presence locally obscures the beam. Beam spatial modulation is thus acquired through diffractive scattering from these obscurations.

We have made careful counts(3) of the number and size distribution of these scattering sites, and we have modeled full nonlinear system performance using the statistical results gleaned from analysis of this data as the spatial noise generator for our system simulation code.(4) The correlation between model calculations and observed near-field modulation is excellent. Figure 1 illustrates this agreement for the Argus laser output beam when operated at three representative power levels. The correlative parameter for best system performance fit to obscuration count statistics is the fractional obscured area per disk surface; this number is typically 5×10^{-5}. Obtaining and maintaining this degree of optical quality is an exacting fabrication and assembly task.

III. Component Damage

All laser chains exhibit an optical damage limit to system output power from a fixed aperture. Components which experience the highest intensity (or fluence) in current laser amplifiers are the input lenses of spatial filters. It is desirable to antireflection coat these lenses in order to minimize Fresnel losses (typically 4% per surface); however, present state-of-the-art AR coatings exhibit damage thresholds typically a factor of two lower than uncoated surfaces. An order of magnitude calculation illustrates the problem clearly.

We ask for the maximum beam energy in a 1 nsec pulse at the output of a spatial filter whose entrance aperture is 20 cm diameter, without damage to the entrance lens. If this lens is AR coated, a typical damage threshold is 8 J/cm^2. Proper optical design (i.e., image relaying) and frequent spatial filtering will minimize, but not eliminate, spatial modulation. Experimental measurements with typical Argus and Shiva beams indicate, in fact, that peak-to-average modulation is on the order of 2:1 for fluences of a few joules per square centimeter; thus one might expect that 4 J/cm^2 average fluence will not damage the input lens. Experiments also show that one can reasonably achieve an 80% filling factor (defined as the ratio of the integral of the beam energy density over its spatial profile to the energy in a flat beam profile completely filling the aperture). Thus one might expect 1000 joules through a 20 cm aperture filter without damage.

Now, if the input lens is left uncoated, the damage threshold is typically 16 J/cm^2. Repeating the above calculation, one finds that 1800 joules can be transmitted through the same filter for the same risk of damage (assuming 90% transmission). In fact, the output lens can be AR coated if the beam expansion ratio of the spatial filter exceeds 1.34. In practice, this strategy will require more energy storage and performance from the amplifiers for equivalent output performance. However, the benefits are so significant that the concept of expanding spatial filters, with entrance lenses uncoated, has been incorporated throughout the Nova laser design.

IV. Aberrations

Residual Seidel aberrations -- astigmatism, coma and spherical aberrations -- in optical components are transferred to the beam as it traverses the optical amplifier chain. Surface figuring of individual components results in (typical) aberrations less than 1/20 wave for components of less than 10 cm clear aperture; and less than 1/10 wave for components of less than 20 cm clear aperture. Assuming that these aberrations influence the beam in an uncorrelated manner, one estimates that Argus and Shiva beams exhibit less than one wave of aberration.(5) Examination of CW alignment beams indicates that this assumption is correct. However, for pulse operation, the focal spot is additionally broadened by intensity dependent nonlinearities. For example, the 90% included power half-angle α for Argus or Shiva at 2 TW is calculated to be 70 μrad; this spread in angle is caused by nonlinear propagation. (For a diffraction limited beam of 20 cm clear aperture, $\alpha \sim 25$ μrad.) Inclusion of one wave of (spherical) aberration in the calculation causes an additional spread to 90 μrad; observed angular spread(1) is approximately 100 μrad. The interplay between distributed aberrations and nonlinear propagation in contributing to angular spreading has not, as yet, been fully resolved. In practice, the most persistent of the Seidel aberrations is residual astigmatism. Aberrations can be partially compensated at smaller apertures near the beginning of each amplifier(6) chain.

For Nova, with its larger apertures, longer chains, and increased number of surfaces, surface figure specifications are expected to become increasingly stringent. Since 5.5 meter focal length lenses (f/11) are planned for Nova target illumination, one concludes that aberrations and nonlinear effects must be reduced as far as possible.

V. Acknowledgements

The author thanks Dr. Irving Stowers and Dr. David Milam for permission to use unpublished results on, respectively, disk obscuration counts and surface damage fluence. He is indebted to W. E. Warren for development of, and extensive calculations with, the Malaprop II-D simulation/propagation code.

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Figure 1

Argus output beam profiles at 1, 2 and 3 TW. The bottom traces represent linearized scans through the diameter of each of the beam photographs shown at the top. The center traces show computer generated scans for each power level, the only variable changed for these three simulations is the chain input power. The agreement in predicted and observed modulation depths is excellent.