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OPTICAL COMPONENTS FOR THE SHIVA LASER*

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ABSTRACT

SHIVA, the 10-kilojoule Neodymium-glass laser for the High Energy Laser facility at Lawrence Livermore Laboratory has been built, exceeded minimum energy predictions, and is currently being applied to laser fusion experiments. The twenty, 20-cm aperture arms contain a total of about 1500 optical components for beam propagation, and another 1000 elements are used for control systems and diagnostics. In order to focus the energy on targets smaller than 1 mm in diameter, it has been necessary to maintain very high optical quality throughout the system. The manufacturing and testing technologies involved in meeting this challenge have been noteworthy and have encompassed glass manufacturing, optical finishing, and coating, for elements as diverse as Faraday rotators, laser rods and disks and aspheric lenses.

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OPTICAL COMPONENTS FOR THE SHIVA LASER

I. INTRODUCTION

The SHIVA Laser has been designed and built at Lawrence Livermore Laboratory (University of California/DOE) as part of the High Energy Laser Facility (HELFF) for inertial confinement laser fusion experiments. It is a Neodymium doped silicate glass laser system operating at a wavelength of $1.064 \mu\text{m}$ with pulse lengths between 0.1 and 3 nanoseconds. SHIVA's 20 arms have a capability of producing in excess of 10 kilojoules of energy in less than 1 nanosecond. On November 18, 1977 all 20 arms were fired simultaneously and yielded 10.2 KJ in 0.9 nanosecond; higher energies are expected as the system operation is optimized.

II. CONFIGURATION AND NUMBER OF COMPONENTS

The system is in two main sections: the laser bay containing the laser proper, and the target bay containing the turn mirrors and focusing optics, the target chamber and most of the diagnostic assemblies. The length of the optical train from the oscillator to the focus in the target chamber is about 132 m, containing approximately 3.9 m of glass, of which 3.3 m is laser glass.

In order to amplify, propagate, and focus the laser energy on very small targets, it is necessary to maintain high optical quality throughout each beam. Since these beams contain many elements, individual component tolerances are very tight.

After the beam leaves the oscillator a few millimeters in diameter, it remains a single beam through a complex chain containing preamplifiers, beam expanders and various other components, thence to a beam splitter section creating four beams which are again amplified. Each of these four beams is distributed via beam splitters to five arms.¹

At the input to each of these twenty arms the beam diameter is 21 mm and the output beam diameter is 202 mm. (The edge of the beam is defined as the 10^{-3} intensity level). As normally operated, for pulse lengths of one nanosecond, the energy at the input of the 21 mm rod is about 0.02 Joules,

and at the output of the 202 mm disc amplifier will be approximately 750 Joules.

In round numbers, the SHIVA system contains about 2500 individual optical components not including about 25% spares. 1500 elements are for propagating the laser beam, and 1000 are for alignment, control, and diagnostics.

In the section from the oscillator to the stage at which the laser splits into four beams, there are about 70 laser optical elements; then, in each beam of the four beam section there are approximately 15. Starting from the beam splitter array, the laser optical elements in each of the twenty arms are as follows:

<u>Component</u>	<u>No. of Optical Elements per Arm</u>	<u>Nominal Output Beam Diameter</u>	<u>Typical Achieved or Estimated Peak to Valley Wavefront Quality per Assembly at 1.064 μm</u>
Beam Splitter	1	21 mm	$\lambda/19$
Path Adjustor Mirrors	2	21	$\lambda/14$
Front End Relay	2	21	$\lambda/12$
Rod Amplifier	1	21	$\lambda/10$
Polarizer	2	21	$\lambda/8$
Pockels Cell Assembly	3	21	
Polarizer	2	21	
Spatial Filter	2	44	$\lambda/12$
Rod Amplifier	1	44	$\lambda/10$
Polarizer	2	44	$\lambda/7$
Pockels Cell Assembly	3	44	
Polarizer	2	44	
Spatial Filter	2	91	$\lambda/12$
Disk Amplifier	6	91	$\lambda/10$
Disk Amplifier	6	91	$\lambda/10$
Polarizer	2	91	$\lambda/9$
Faraday Rotator	1	91	
Polarizer	2	91	

<u>Component</u>	<u>No. of Optical Elements per Arm</u>	<u>Nominal Output Beam Diameter</u>	<u>Typical Achieved or Estimated Peak to Valley Wavefront Quality per Assembly at 1.064 μM</u>
Spatial Filter	2	91	$\lambda/12$
Disk Amplifier	6	91	$\lambda/10$
Spatial Filter	2	145	$\lambda/12$
Disk Amplifier	4	145	$\lambda/10$
Spatial Filter	2	202	$\lambda/12$
Polarizer	1	202	$\lambda/9$
Faraday Rotator	1	202	
Polarizer	1	202	
Disk Amplifier	3	202	$\lambda/8$
First Turn Mirror	1	202	$\lambda/14$
Second Turn Mirror	1	202	$\lambda/15$
Focus Lens	1	202	$\lambda/7$
Vacuum Window	1	185	
Blast Shield	1	185	

$$69 \times 20 = 1380$$

Figure 1 shows a variety of SHIVA optical components.

III. TYPES OF COMPONENTS

There are eight types of optical materials in the laser (plus a liquid dye cell).

1. Yag (oscillator)
2. BK-7 (lenses, mirrors, polarizers, substrates, etc.)
3. KD*P crystals (Pockels Cells)
4. Crystal Quartz (small diameter rotators and wave plates)
5. Fused Quartz (some small substrates)

6. Nd-doped silicate laser glass (rods and disks)
7. Tb-doped silicate Faraday rotator glass
8. Neutral Density Glass (calorimetry diagnostics)

The majority of the surfaces are flat, but there is a large number of $f/11$, $f/6$, and $f/2.8$ lenses which are aspherized for the removal of spherical aberration. Components which transmit the beam were kept as thin as practicable in order to reduce the effects of the non-linear index of refraction of the glass.² For almost all the flat components, very effective use was made in industry of modern thermally controlled continuous polishing flat lapping techniques.³ For the aspheric surfaces, the companies involved developed quite efficient techniques for figuring and in process testing. With one exception (the set of 220-mm aperture $f/2.8$ lenses for alignment and focus control, which required about 120 μm of asphericity) the surfaces were ground and polished spherical before figuring. In the case of the $f/2.8$ lenses the surfaces were aspherized in the ground state.

The different types of thin film coating requirements were:

1. Antireflection coatings on laser rods, Pockels cell window exteriors, lenses, windows, Faraday rotators, and on the back surface of beam splitters.
2. Beam splitter coatings on many relatively small front end and diagnostic components (including some reflecting attenuators) and on the most massive single optical element in the laser, the second turn mirror. This optic, which is 374 mm in overall diameter and 80 mm thick is made from "PH-4" quality BK-7 and in addition to turning the high energy laser beam, is used as a 3.5% transmitting beam splitter for precision incident beam and reflected beam diagnostics.
3. High reflectance coatings on various smaller optics, and on the large turn mirrors and diagnostics folding mirrors.
4. Polarizer coatings.

Thus, most of the optical surfaces in the laser receive a thin film coating, the principal exception being the laser disks which are used at Brewster's Angle. These however, are edge clad (thick film glassy frit) to absorb 1.064 μm light for the suppression of parasitic modes.²

IV. TOLERANCES AND SPECIAL CHARACTERISTICS

Through previous development programs and the building and operating of the CYCLOPS and ARGUS lasers, the LLL Laser Program had built a background of confidence in the basic physics performance capabilities of the type of optical components required for SHIVA, and in the ability of industry reliably to produce such components to the uniformity and quality required. Nevertheless, the size, time scale, and tight tolerancing of the SHIVA optics procurement provided a substantial challenge.

The tolerance levels of these components can be well illustrated by some selected specification given in Figure 2. In many instances, these specifications are the tightest that appeared feasible in the context of budgetary and schedule constraints, or the state of the art.

The determination of performance characteristics and final specifications was often the result of extensive technical interaction between LLL and the participating vendors involving prototype development and qualification tests.

V. MODES OF PROCUREMENT

The simplest type of procurement is to buy a completely finished component from a single vendor. In general, the SHIVA components require three distinct sequential stages of manufacture: 1) optical material 2) optical finishing and 3) thin film coating (Except for the laser disks; the relatively thick glassy edge cladding of the laser disks is really part of the material manufacture, as the fine annealing of the blank occurs after the cladding is applied).

The practicality of obtaining finished components from a single vendor depends on vendor capability, the relative cost and state of the art for these three operations for the component in question, and on scheduling.

It is often practical when:

- a. the vendor can do the entire operation or,
- b. the part he has to subcontract is reasonably low risk, and inexpensive, or relatively inexpensive compared to the operation he does himself and
- c. exact requirements and specifications are known sufficiently well in advance of delivery needs so that there is time for a vendor to be responsible for subcontracting long lead items.

The total optical component procurement for SHIVA was approximately \$6,000,000; of this, about 57% was bought as finished parts:

Most flat BK-7 optics for 10 cm beam diameter and under	~ 5%
Laser glass rods and disks	~ 40%
Faraday rotator elements	~ 8%
Pockels Cell assemblies	~ 4%
	~ 57%

For the first set of items, the finishers or coaters (frequently within the same organization) were the prime contractors. For the last three items, the material manufacturers were the prime contractors. For the remaining 43% of the optics (large polarizers, mirrors, windows, focusing lenses, and all the spatial filter lenses), each manufacturing stage was separately subcontracted by LLL.

V1. QUALITY CONTROL PROGRAM

Most of the inspection of optical components was done under a source inspection program at the optical vendors. One hundred percent inspection of certain critical characteristics, along with appropriate documentation, was specified on the drawings. The documents were forwarded in duplicate to LLL where one remains on permanent file in the Laser Optics Depot, and the other travels with the component. On virtually all first runs, and on a frequent spot check basis thereafter, these inspections were witnessed by experienced technical people from LLL (usually including one or more of the authors).

This system worked extremely well; if there were problems with manufacture, test, equipment, or interpretation they could usually be dealt with "real time" as the parts were generally right off the production line. For equivocal cases, the part was sent to the test facility at LLL for retesting and review. This eventually helped to standardize the test equipment and data interpretation as applied to SHIVA optical components.

In some instances exceptions were made to the principal of source inspection. One example was the testing of wavefront quality for large aperture optics after coating, where the coating vendor's current interferometry did not include the diameter required. In this case the parts were tested for wavefront after coating at LLL. Another is the case of laser damage testing, where LLL has unique calibrated facilities for the appropriate wavelengths and pulse durations.

One additional final test has been performed on all SHIVA optical components. Each subassembly (e.g., laser head, spatial filter, mounted mirror) is tested for wavefront, (and where appropriate, stress birefringence), before installation in the laser. For this purpose two interferometers are available in one of the LLL laser assembly areas, a 30-cm aperture 0.633 μm Zygo Fizeau with a special long bed, and a 30-cm aperture 1.06 μm LLL built Twyman-Green (residing on a 25 ton granite slab).

VII. RESULTS

At this writing, essentially all of the optical fabrication has been completed except the coating of the 20-cm aperture polarizers, which is underway. The components have been delivered promptly enough so that to date, all the program milestones have been met. Within the next several weeks, after target shots begin, extensive quantitative data on the optical focussing quality of each arm will be available; preliminary data obtained through one arm at the output of the 20-cm aperture spatial filter indicates a blur circle of about 0.05 milliradians diameter at the focus of an $f/6$ lens, a cumulative wavefront error of about one wave at 1.06 μm wavelength. This was achieved firing at an energy level of about 500 Joules. These are similar to the results achieved on LLL's CYCLOPS, a single arm 20-cm

aperture prototype laser, and ARGUS, a similar 2 arm laser currently in use at LLL for laser fusion experiments.

The ability to achieve these results depends on appropriate laser design, careful assembly, and of course, the quality of the individual components. As indicated above, the tolerances are tight; on the average, the results for wavefront are better than the *minimum* specifications.

Figures 3a, 3b, and 3c show typical wavefronts of some of the larger components.

VIII. ACKNOWLEDGEMENT TO OPTICAL COMPONENT MANUFACTURERS

We heartily thank all the vendors who have worked so hard to meet these rigorous state of the art requirements, for the production of these components has been their achievement. In particular, the major manufacturers for this phase of the SHIVA Optics procurement were: Cleveland Crystals, Continental Optics, Hoya, Lasermetrics, Optical Coating Laboratories, Opti-Systems, Owens Illinois, Perkin-Elmer, Schott Optical, Spectra Physics, Tinsley, and Zygo. In addition, Battelle assisted with disk edge cladding development.*

*Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the United States Department of Energy to exclusion of others that may be suitable.

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Figure 1:- A variety of SHIVA optical components. The three sizes of laser disks are shown at the top, along with two Pockels cell assemblies. In the front foreground is a 212 mm aperture spatial filter lens.

TOLERANCE CHART

APERTURE SIZE	10 CM			20 CM		
	DISKS	SF LENS	POL	DISKS	SF LENS	POL
INCLUSIONS/100 CC	.03 mm ² 0.125 Max dimension	.03 mm ² 0.100 max dimension	.03 mm ² 0.100 max dimension	.03 mm ² 0.2 Max dimension	.03 mm ² 0.2 max dimension	.03 mm ² 0.2 max dimension
STRESS BIREFRINGENCE nm/cm	2.5	6.0	2.0	5.0	6.0	6.0
WAVEFRONT P.V. = 0.633 λ After coating when applicable	± 12	± 10	± 12	± 10	± 10	± 8
WAVEFRONT SLOPE/CM 0.633 λ	± 30	± 33 to ± 22	± 30	± 40 to ± 22	± 33 to ± 22	± 30 to ± 20
AR COATING REFLECTIVITY	-	0.1	-	-	0.1	-
THIN FILM POLARIZER P TRANSMISSION	-	-	95	-	-	96
S TRANSMISSION	-	-	1.5	-	-	1.5
THIN FILM COATING DAMAGE	-	$\leq 30 \text{ GW/CM}^2$ $\leq 0.1 \text{ NSEC}$ in 0.1 NSEC, $\leq 0.1 \text{ GW/CM}^2$ in 1.0 NSEC	$\leq 40 \text{ GW/CM}^2$ $\leq 0.1 \text{ NSEC}$ in 0.1 NSEC, $\leq 0.1 \text{ GW/CM}^2$ in 1.0 NSEC	$\leq 30 \text{ GW/CM}^2$ $\leq 0.1 \text{ NSEC}$ in 0.1 NSEC, $\leq 0.1 \text{ GW/CM}^2$ in 1.5 NSEC	$\leq 40 \text{ GW/CM}^2$ $\leq 0.1 \text{ NSEC}$ in 0.1 NSEC, $\leq 0.1 \text{ GW/CM}^2$ in 1.0 NSEC	$\leq 7 \text{ GW/CM}^2$ $\leq 0.1 \text{ NSEC}$ in 0.1 NSEC, $\leq 0.1 \text{ GW/CM}^2$ in 1.0 NSEC

Figure 2

Figure 3a An Interferogram showing the 208 mm diameter aperture (double pass at $0.633\mu\text{M}$) of a Nd doped laser disk at Brewster's Angle. The disk is 32 mm thick and its exterior shape is a 223 by 418 mm ellipse. (Opti-Systems).

Figure 3b . An Interferogram of a SHIVA focusing lens (also used in incident beam diagnostics assembly). This is a single element $f/6$ BK-7 lens shaped for minimum coma and corrected for spherical aberration by an aspheric on the front (more curved) surface. The clear aperture shown is 210 mm (slightly larger than the beam diameter); at this aperture the f/no is 5.8, requiring about $9\mu\text{M}$ of asphericity on the surface. The interferogram is double pass at $0.633\mu\text{M}$. (Tinsley).

Figure 3c - A Double pass Fizeau Interferogram in transmission at $0.633\mu\text{M}$ showing the 218 mm clear aperture of a polished (but uncoated) polarizer substrate at Brewster's Angle (56.43 degrees angle of incidence for BK-7 at $1.064\mu\text{M}$). The beam projected on each surface is an ellipse 394 by 218 mm, while the thickness of the part is only 10 mm. The inner circle inscribed on the interferogram represents a zone over which the slope error tolerance is tighter. (Perkin-Elmer).

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