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BEAM TRANSPORT OPTICS FOR LASER FUSION*

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ABSTRACT

The performance of large laser systems for laser fusion is limited by self-induced damage to optical components, arising from the interaction of the intense light with the optical materials in the laser system. In the design of the beam transport optics, due consideration must be given to high intensity effects, including self-focusing, surface damage, and internal reflection focusing. The constraints imposed on the design of optical components by these considerations are discussed.

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The reader will find the preceding paper,[1] dealing with the status of the Shiva laser, very impressive. The degree and manner in which you are impressed depends on your point of view. If one is a laser builder, one is impressed by the challenge. If one is a components manufacturer, one is impressed by the opportunity. As a taxpayer, one cannot help but be impressed by the expense.

In the design of a system of this complexity and expense, every aspect of the system must receive careful attention, and every effort must be made to achieve the optimal design. This paper deals with only one aspect of the system, beam transport optics. By this we mean those passive optical elements, lenses, mirrors and polarizers, which transport the energy throughout the laser system, and bring it to a focus on the fusion target.

In Table I we see the number of such components in the Shiva system, as described in the previous paper. We see that there are 277 lenses in Shiva, including relays, spatial filters, and the target chamber. No focusing mirrors are used in Shiva, but the system contains 115 flat mirrors, mostly beam steering and turning mirrors. The lenses and mirrors are all dielectric coated elements, the lenses coated for low reflection, the mirrors for high reflectivity. With polarizers and beam splitters, there are about 1000 coated surfaces in Shiva, ranging in aperture from a few cm up to 20 cm in diameter.

Table I - Number of SHIVA Components

Laser Disks	625
Laser Rods	61
Polarizers	355
Beam Splitters	26
Rotators	50
Folding Mirrors	63
Turning Mirrors	52
Spatial Filter Lenses	200
Focusing Lenses	50
Pockels Cells	50
Beam Expanding Lenses	27
	1,559

All of the Shiva components have been manufactured, and most are already in place at the Lawrence Livermore Laboratory. We are, however, in the process of designing the Nova system, which will generate an output energy power ten times that of Shiva.[2] Of course, Nova will not simply be ten Shivas, but the list of parts will comprise a total number of components from two to four times as great as that given for Shiva in Table I. The magnitude of the problem of procuring and maintaining an adequate inventory of optical elements for a large fusion laser like Nova is far greater than anything previously encountered in laser optics.

It is not enough simply to obtain all these expensive optical elements, either. An additional requirement is that of reliability, or in this case, survivability. One cannot afford to replace any significant fraction of these thousands of elements on every shot. The ultimate limitation to the performance of any large laser system designed for energy delivery, either at high average power or high peak power, is damage to the optical components. Stringent tolerances must be met in the manufacture of the components, in order to maintain beam quality in the system, and phase distortion, due either to thermal lensing or nonlinear index effects, limits respectively the average power and peak power at which the system can operate, but the overriding consideration for the survivability of the system is the self-inflicted damage to optical components due to the high energy density in the propagating laser beam. These are the problems the laser designer must keep in mind in designing an energy delivery laser system.

Target Illumination Optics

Let us examine the target illumination optics designed for laser fusion experiments at the Lawrence Livermore Laboratory. The Janus laser, which became operational in 1974, puts out 0.2 TW per arm in a pulse of 150 psec, from two apertures of 85 mm diameter. The "clamshell" illumination scheme was first proposed by C. E. Thomas[3] of KMSF, and was adapted for use on Janus. In Fig. 1, we see a schematic of the clamshell arrangement. The light is focused into the clamshell interior through a fast doublet of N. A. 0.7. As larger and more powerful lasers were developed, it was not sufficient simply to scale this design up for higher power. The accumulated nonlinear phase distortion in the focusing doublet would have been too great. Instead, the "Compound Clamshell" was designed, in which the required refractive power was reduced by introducing a secondary focusing mirror. (After the "Compound Clamshell" was designed, it was pointed out, by David Shafer,[4] of Perkin-Elmer, that a single ellipsoidal surface could be employed in a multiple-bounce configuration, to provide the same effect as multiple ellipsoidal mirrors.) The compound clamshell is shown in Fig. 2, as it was envisioned for the Argus laser. Argus started operation in 1976, radiating 1.5 TW in 150 psec from each of two, 200 mm diameter apertures. It is currently radiating nearly 5 TW from the same aperture. However, the compound clamshell configuration has not been implemented.

Shiva will begin to irradiate targets in 1978, at a power level of 1 TW from each of twenty, 200 mm apertures. The Shiva target chamber is seen in Fig. 3. We note immediately the relatively simple optics involved in the target illumination system. This simplicity can be attributed to two causes. First, the physics of the interaction of intense light with the target plasma is much better understood than it was three years ago, and experiments have shown that uniform illumination of the target over 4π steradians is not required for successful implosion. Second, the use of a large number of beams in the system allows much slower lenses to be employed. The Shiva lenses are f/6 aspheric doublets, not exactly off-the-shelf items, but far less demanding than the lenses required by the clamshell configuration. We see then that the need for the esoteric lens designs of a few years ago has been diminished by the availability of much more powerful lasers.

Laser Damage

There are two limits to the performance of laser systems imposed by the interaction of the intense light with the optical materials in the beam transport optics and laser media. For sub-nanosecond pulses, the performance limit on a given laser is set by the so-called B-integral,[5] the cumulative phase shift along the optical path due to the intensity-dependence of the refractive index. If we write the refractive index in an optical medium as

$$n = n_o + n_2 < E^2 > \tag{1}$$

where $< E^2 >$ is the mean square electric field in the light wave, then the integrated nonlinear phase displacement is given by

$$B = (2\pi / \lambda_o) \int d\ell \, n_2 < E^2 > \tag{2}$$

JANUS SPHERICAL ILLUMINATION SYSTEM

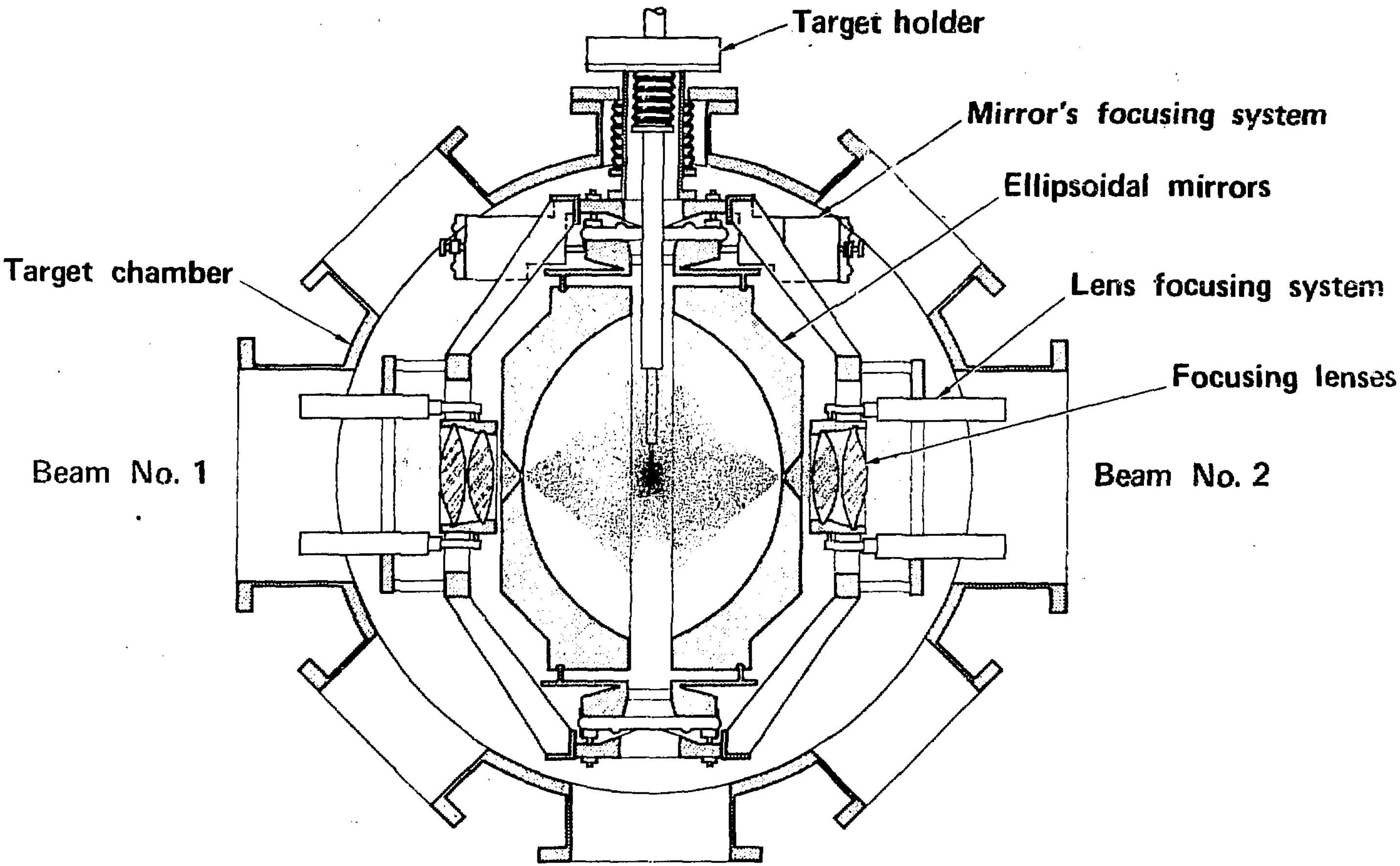

Figure 1.

ARGUS SPHERICAL ILLUMINATION SYSTEM

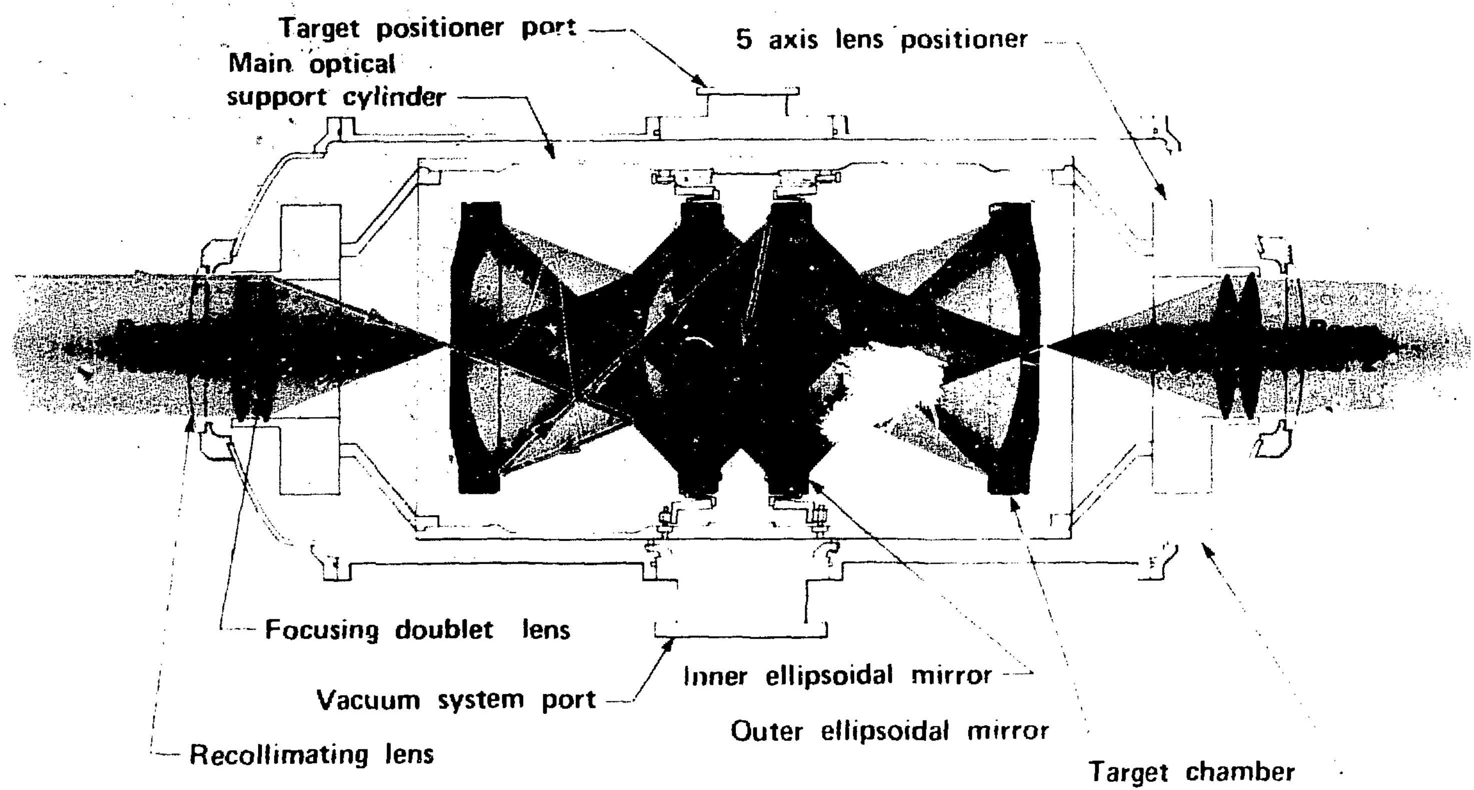

Figure 2.

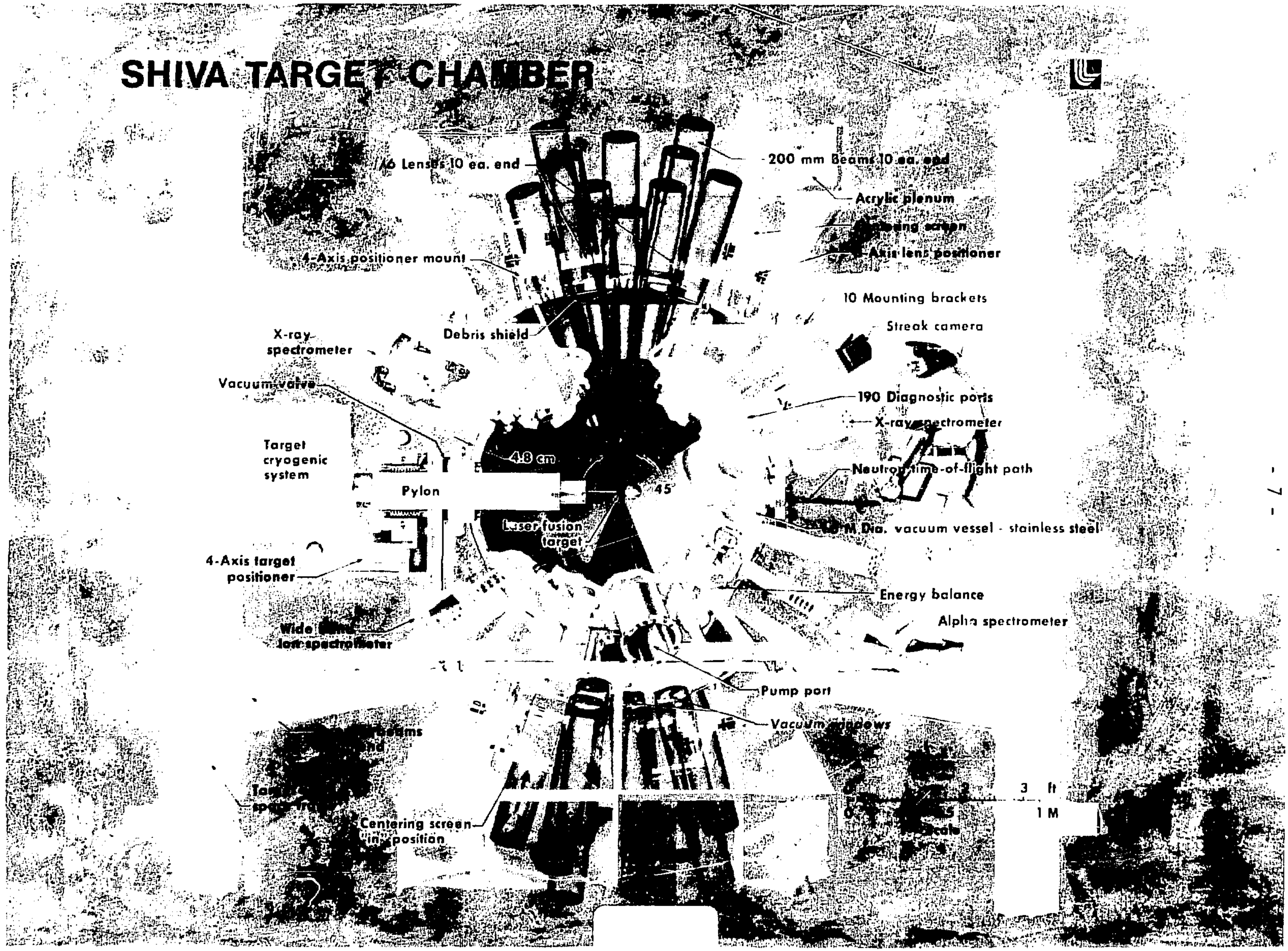
SHIVA TARGET CHAMBER
f/6 Lenses 10 ea. end
200 mm Beams 10 ea. end
Acrylic plenum
4-Axis positioner mount
10 Mounting brackets
Streak camera
Debris shield
X-ray spectrometer
Vacuum valve
190 Diagnostic ports
X-ray spectrometer
Target cryogenic system
4.8 cm
Pylon
45°
Neutron time-of-flight path
Laser fusion target
M Dia. vacuum vessel - stainless steel
4-Axis target positioner
Energy balance
Alpha spectrometer
Pump port
Vacuum windows
Centering screen in position
3 ft
1 M
Scale

Figure 3.

in units of the vacuum wavelength. Since the intensity is given by

$$I = n_o < E^2 > c/4\pi \tag{3}$$

we can write

$$B = (2\pi / \lambda_o) \int d\ell \, \gamma \, I \tag{4}$$

where the coefficient γ is given by

$$\gamma = 4.189 \times 10^{-11} \, (n_2 / n) \tag{5}$$

with n_2 in 10^{-13} esu, and I in GW/m^2.

It has been shown by Bespalov and Talanov[6] that an intense beam, propagating in a medium, with an intensity-dependent index of the form of equation 1, is unstable against small perturbations of phase and amplitude. The growth rate of the most unstable spatial frequency is also given by the quantity, B. By the introduction of spatial filters throughout the system, the buildup of spatial variations of phase and amplitude can be suppressed.

Moreover, in the choice of optical materials, both laser materials and optical elements, materials of lower refractive index, which have concomitantly lower nonlinear index values, are preferred. We shall see, subsequently, the kind of improvement which can result from choosing new optical materials of lower refractive index.

As the pulse length is increased to one ns or beyond, laser amplifiers are limited by the effect of gain saturation. Here again, by suitable choice of materials, the system performance can be markedly improved. One would like to use laser materials with a low value of the stimulated emission cross-section, so as to raise the saturation fluence, and also to be able to use larger aperture systems without significant amplified fluorescence losses.

Thus at subnanosecond pulse durations, we are limited by the value of the index nonlinearity, while at the nanosecond durations or longer, amplifier saturation limits the possible performance. Moreover, both these parameters can be modified by the appropriate choice of materials. However, once these choices have been made, systems performance is limited by the physical damage of coated elements in the intense laser beam. There is a critical value of the fluence which, if exceeded, leads to damage on coated elements. This critical fluence, which varies from material to material, has been observed to vary as the square root of the pulse duration.[7] Thus, if a certain damage level is observed at on nsec, called J_1 then at a pulse duration t_p, the damage level will by given by $J_1 \sqrt{t_p}$. This scaling relation, although empirical, is observed to hold over a wide range of experimental conditions.

In Table II, we see the results of measurements of laser damage thresholds at 0.125 nsec from Milam et al.[8] Although there is significant variation from sample to sample, the average values lie in the vicinity of 4 J/cm^2. Damage thresholds in metal mirrors at this pulse duration can be raised to this value as well, by appropriate preparation. But this does not mean that a system can be designed to operate at 4 J/cm^2 in 0.125 ns, or equivalently 11.3 J/cm^2 in one ns. One must operate at a level sufficiently below this value to ensure that damage will not occur. The appropriate margin of safety, in turn, depends on the B-integral in the system, since at higher B values, the spatial modulation of the beam is greater. Currently, our designs assume that a "safe" operating level at one ns is from 4 to 6 J/cm^2. We are striving to improve the damage resistance of thin film coatings, in order to increase the fluence at which our systems can operate.

Table II - Damage Thresholds for Polarizing Dielectric Films

	Threshold (J/cm^2 at 125 $\pm$ 25 ps)[a]	
Sample	P-polarization	S-polarization
1	5.5 ± 1.0	3.3 ± 0.7
2	3.0 ± 0.5	5.0 ± 1.0
3	2.7 ± 0.5	1.0 ± 0.2
4	5.3 ± 0.5	5.0 ± 1.0
5	-	9.0 ± 1.5
6	-	1.2 ± 0.3
7	-	1.3 ± 0.3
8	-	5.4 ± 1.0
9	2.5 ± 0.5	3.3 ± 0.5
10	3.2 ± 0.5	3.4 ± 0.5
11	5.9 ± 1.5	7.0 ± 1.0
12	2.9 ± 0.5	1.1 ± 0.3
13	3.8 ± 0.5	2.2 ± 0.5
14	5.3 ± 1.0	1.7 ± 0.4
15	3.6 ± 0.5	3.9 ± 0.5
16	3.3 ± 0.5	4.1 ± 0.7
Average Values	3.92	3.62

[a] Energy densities are these in a plane perpendicular to the beam. Polarizers were at Brewster's angle relative to the input beam for both S and P tests.

Lens Design for High Power Lasers

In the past few years, the laser program at Lawrence Livermore Laboratory, in conjunction with the ERDA materials program under Dr. Joel Weiss's able direction, has emphasized the development of new materials for high power laser optics. As an illustration of the benefit accruing from choice of materials, we see in Table III a list of optical materials, along with their values of n_0, n_2 and the lens figure of merit, $n(n-1)/n_2$.[9] This figure of merit relates the refracting power of the lens to the B-integral contribution through the lens. We choose the borosilicate glass BK-7 as a standard, normalized to unity. We see that by going to fluorophosphate glass, or CaF_2 crystal, we can raise the lens figure of merit by a factor of 1.7 to 1.8. Even greater improvement can be achieved, if we can overcome the difficulties of fabrication of some of the lower index materials.

Table III - Refractive Indices and Relative Figure of Merit for Lens Materials at 1064 nm

GLASSES	TYPE	n_0	n_2 (10^{-13} esu)	Figure of merit: $n(n-1)/n_2$
Borosilicate	(BK-7)	1.517	1.24	1.0
Fused Silica	(SiO_2)	1.458	0.95	1.1
Fluorosilicate	(FK 5)	1.487	1.0	1.1
Fluorophosphate	(FK 51)	1.487	0.69	1.7
Fluoroberyllate	-	∿1.35-1.40	∿0.4	2.0
Crystals				
CaF_2	(cubic)	1.434	0.57	1.8
LiF^2	(cubic)	1.392	0.35	2.5
MgF_2	(tetragonal)	1.378 (o) 1.389 (e)	0.30	-

After the nonlinear index is fixed by the choice of material, the evaluation of the B-integral through the lens must take account of the intensification of the light in the lens. This seems like an obvious point, and the calculation turns out to be trivial, but the result has been overlooked in many lens designs. It can be shown that the B-integral through a lens with index n, nonlinear coefficient γ, and incident intensity I is given by[10]

$$B = (2\pi/\lambda)\,\gamma\, I\, t_{eq} \tag{6}$$

where the equivalent thickness of the lens is given by

$$t_{eq}^{-1} = t^{-1} + (ns)^{-1} - (n-1)/n R_1 \qquad (7)$$

where t = lens thickness
R_1 = radius of curvature of the first lens surface
S = radius of curvature (vergence) of the incident beam phase surface, taken positive if diverging. By application of the lens equation, this formula can be applied to a series of lenses. Note that, even for aspheric lenses, the effective thickness t_{eq} can be determined simply from the vertex curvature of the lens.

Finally, I want to mention one of the specialized computer codes developed at the Lawrence Livermore Laboratory for the analysis of high power laser lens designs. We have been using the commercial design code, ACCOS V,[11] for routine lens designs, and, when our design problems involved difficult aspheric surfaces, we used internally developed, point design codes.[12] We found that there was no readily available computer code for the analysis of caustic formation due to internal reflections in lenses, so we had to develop a code for this purpose. The code is called Ghost, and was developed by John Trenholme and Ed Goodwin.[13]

An example of the application of the Ghost code is shown in Fig. 4. Here we see an f/1 lens used with the Janus laser system. The pattern of damage which was observed after a period of use is seen to be made up of two crescents lying on a circle near the central hole in the lens. (A hole is drilled along the optic axis of the lens to prevent damage due to on-axis caustics.)

The Ghost analysis is shown in Fig. 5. We see that an off-axis caustic forms due to Fresnel reflection from the second surface of the lens, followed by total reflection from the rear surface. The reason for the crescent shape of the damage pattern is now apparent. The reflected intensity is dependent on the polarization of the incident light, so in the plane of least reflection, no damage appears. Furthermore, only rays near the outer edge of the lens contributed to the damage, since rays nearer the axis are not totally reflected from the rear surface of the lens.

GHOST FOCUS DAMAGE IN LENS

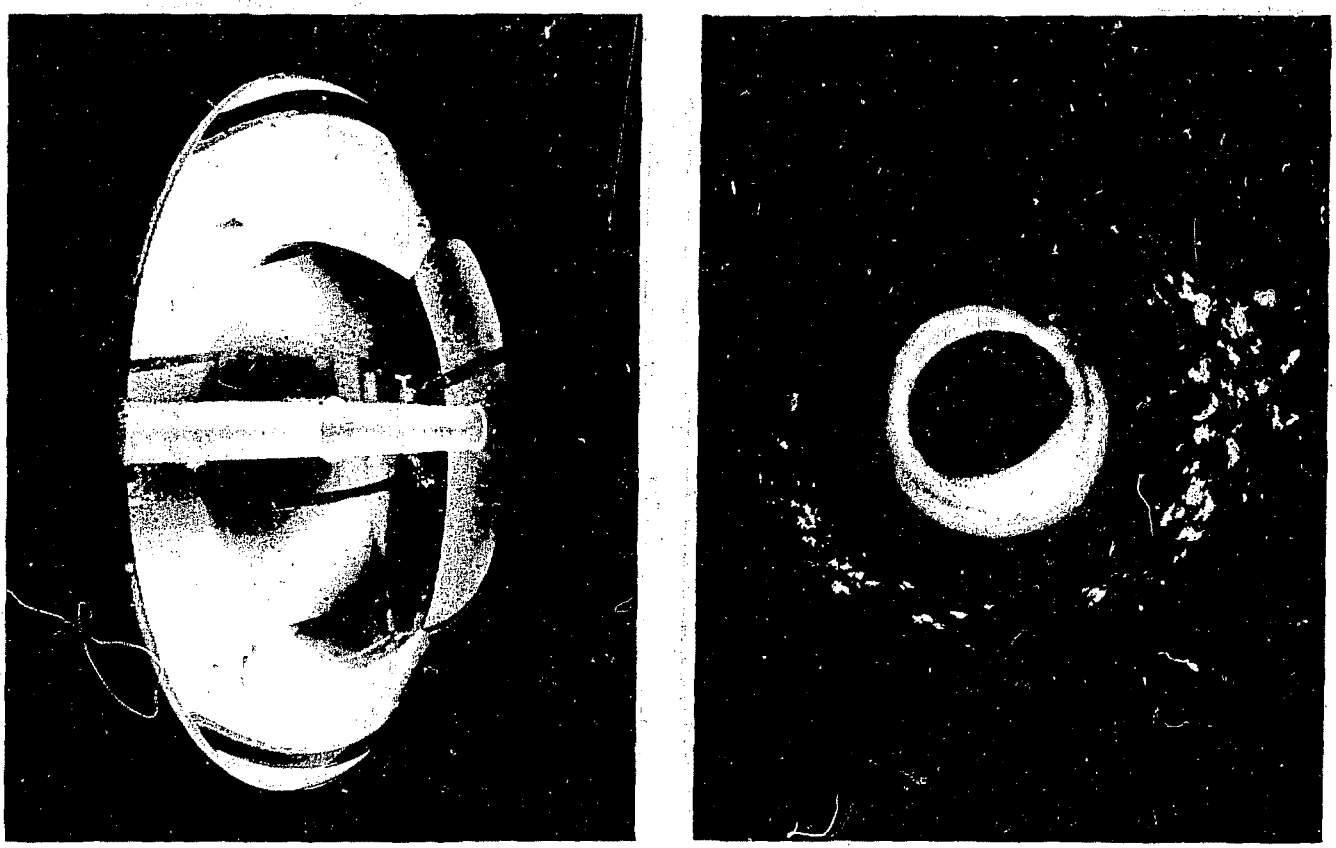

Fig. 4.

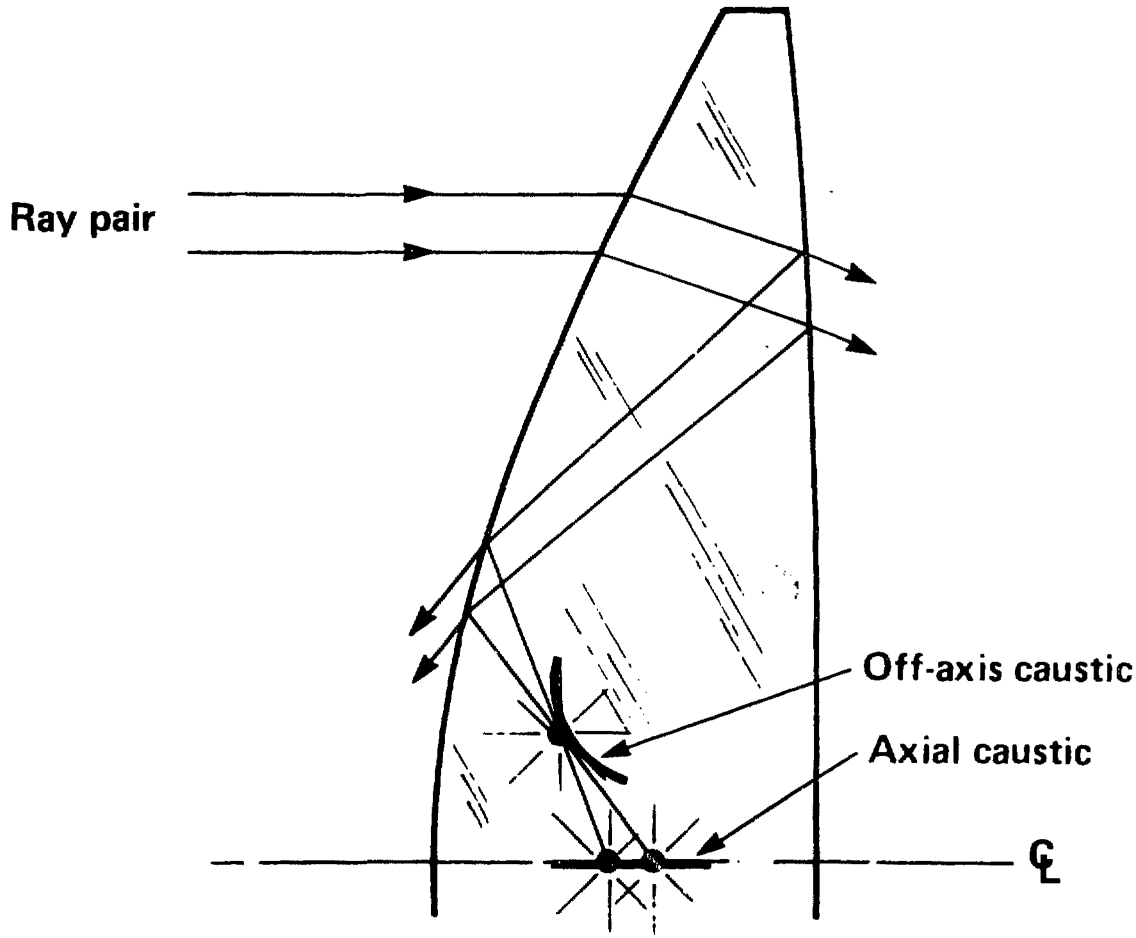

Figure 5.

GHOST FOCI IN THE ARGUS DOUBLET

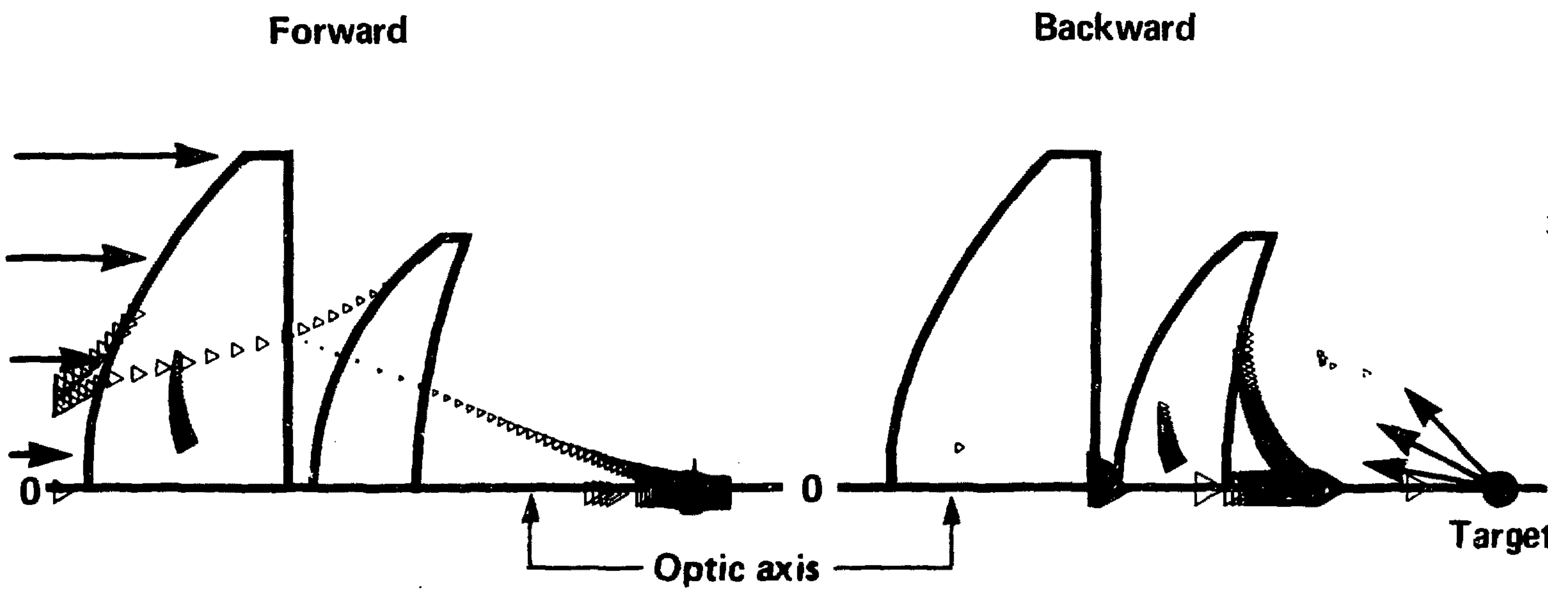

Figure 6.

In Fig. 6, we see the Ghost analysis of a fast doublet lens used with the Argus laser. The size of the triangles represents the intensity of the caustic. The Ghost analysis is carried out for both light incident from the laser, and reflected from the target, since a large fraction of the light can be reflected from the target, and, in the case of opposing beams, if the target is not present when the laser fires, the full power of the opposing beam can be incident on the lens.

We see that the pattern of caustics is complicated, and that potentially damaging caustics appear in both lenses, one on forward incidence, and the other on backward incidence. One must vary the design so as to equalize the intensity in each of these caustics, at which point one has achieved the optimal design.

Conclusions

To summarize, let us reiterate the main points of this discussion. First, as we move to higher laser power, the need for exotic optical designs diminishes. Second, advances in laser and optical materials have markedly improved the performance of large laser systems. Third, as we move to longer pulse durations, large lasers become limited by damage at coated surfaces. Improvements in coating damage thresholds will yield concomitant increases in laser system performance. Finally, simple optical designs, with as few surfaces as possible, are optimal for high power lasers optics, taking into account internal self-focusing and caustic formation.

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