81
8-21-80
J. F. Holzrichter

MASTER

Dr. 1663

UCRL-52868

High-power pulsed lasers

John F. Holzrichter

April 2, 1980

Lawrence
Livermore
Laboratory

High-power pulsed lasers*

John F. Holzrichter

Manuscript date: April 2, 1980

DISCLAIMER

This document contains information which may be proprietary to the University of California. It is to be used for informational purposes only and is not to be distributed outside the University of California. It is to be used for informational purposes only and is not to be distributed outside the University of California. It is to be used for informational purposes only and is not to be distributed outside the University of California.

*A series of lectures for the 20th Scottish University
Summer School in Physics, Laser Plasma Interaction

LAWRENCE LIVERMORE LABORATORY
University of California • Livermore, California • 94550

Available from: National Technical Information Service • U.S. Department of Commerce
5285 Port Royal Road • Springfield, VA 22161 • \$8.00 per copy • (Microfiche \$3.50)

FOREWORD

This report was originally presented as lectures for the 20th Scottish University Summer School in Physics on Laser Plasma Interaction, and is drawn from many sources. Most of the contributions come from my colleagues in the Laser Program at the Lawrence Livermore Laboratory (LLL). Their voluminous output, summarized in the Laser Program Annual Reports from 1973 to the present (UCRL-500021-73 to -78), forms the basis for this work. Workers at the Naval Research Laboratory (Washington, D. C.), at Compagnie General d'Electricite (Marcoussis, France), the University of Rochester (NY), the Lebedev Institute (Moscow), and the Los Alamos Scientific Laboratories (NM), have all made fundamental contributions to the technology of fusion lasers. I would like to acknowledge this influence on these lectures. In particular, I would like to acknowledge John L. Emmett, the Livermore Laser Fusion Program Director, for his encouragement and his innumerable contributions to the design of high-power fusion lasers. I would also like to thank Bill Krupke, who has led the advanced laser group at LLL. Most of the extensions of our laser design ideas beyond ND:glass are attributed to Bill and to his group. John Nuckolls deserves special mention for his work in target physics and its influence on laser design. Hal Ahlstrom's Fusion Experiment Program has made extensive contributions to target physics and to the optical diagnostics of lasers and targets.

In particular I would like to acknowledge my close working associates Thomas J. Gilmartin, Alexander J. Glass, Roger Haas and John B. Trenholme in the Laser Program for their assistance in this work, to Mrs. Patt Page for the preparation of the manuscript, to Mr. Robert Hendrickson for editorial assistance, and I extend my thanks to the members of the Fusion Program listed below:

Laser design

J. A. Glaze
R. A. Haas
W. H. Hagen
W. W. Simmons
J. B. Trenholme

Propagation

E. S. Bliss
A. J. Glass
J. T. Hunt
I. Seppala
W. W. Simmons
W. E. Warren

Laser materials

W. H. Lowdermilk
T. Marchi
D. Milam
W. L. Smith
S. E. Stokowski
E. P. Wallerstein
M. J. Weber
R. Wirtensen

Components

L. Bradley
B. C. Johnson
D. J. Kuizenga
G. J. Linford
W. E. Martin
J. E. Murray
M. A. Summers
S. M. Yarema

Diagnostics and alignment

E. S. Bliss
F. W. Holloway
K. R. Manes
R. G. Ozarski
D. R. Speck
G. Suski
J. E. Swain
P. VanArsdall

Laser engineering and construction

W. L. Gagnon
T. J. Gilmartin
R. O. Godwin
C. A. Hurley
H. G. Patton
F. Reinecker
P. R. Rupert
I. F. Stowers
K. Whitham

CONTENTS

Foreword	ii
Abstract	1
Introduction	1
Laser-Target System	3
Orders of Magnitude	6
Lasers	6
Laser Gain	9
Laser Examples	12
Gain and Saturation	16
Frequency and Bandwidth	21
Focusability	22
Laser Operational Constraints	29
Gain Constraints	29
Chain Stability	29
Target Isolation	31
Transverse Oscillations	31
Amplified Spontaneous Emission (ASE)	31
Losses	34
Nonlinear Optics	34
Self-focusing	35
Damage Limits	39
Linear Phase-aberration Constraints	41
Aperture Size, Fill Factors, and Intensification	41
Coherent Interference	43
Laser Components	45
Oscillators	45
Amplifiers	51
Nd:glass Medium	53
CO ₂ Gas Medium	55
Spatial Filters and Relays	57
Isolators	59
Summary	61
Laser Diagnostics	62
Vital Measurements	62
Laser Systems	66
Generic Systems	66
System Design	68
Summary of Some Rules for Laser-stage Design	70
Staging	70
System Costs	74
The Future	76
References	77

High-power pulsed lasers

ABSTRACT

The ideas that led to the successful construction and operation of large multibeam fusion lasers at the Lawrence Livermore Laboratory are reviewed. These lasers are based on the use of Nd:glass laser materials. However, most of the concepts are applicable to any laser being designed for fusion experimentation. This report is a summary of lectures given by the author at the 20th Scottish University Summer School in Physics, on Laser Plasma Interaction. This report includes basic concepts of the laser plasma system, a discussion of lasers that are useful for short-pulse, high-power operation, laser design constraints, optical diagnostics, and system organization.

INTRODUCTION

With the demonstration of the laser in 1960 came the realization that its light could be focused and used to heat small but significant volumes of matter to temperatures high enough to induce fusion reactions.^{1,2} In the laser, light is generated and propagated at low enough fluence levels so that optical damage to materials can be avoided. Most importantly, almost perfect coherence is retained, permitting focusing of the beam to areas of $\sim \lambda^2$ where λ = laser wavelength. Thus, by focusing the laser output the power density on target can be increased enormously. Using this device, the experimenter can study matter under conditions of pressure, temperature, and density that have been attainable only under much more difficult experimental conditions such as in chemical explosions, hypervelocity gas guns, shock tubes, and nuclear explosions. For example, small targets ($\sim 10^{-7}$ g) are routinely heated to 1 keV (10^7 K) with 10 J, 0.1-ns laser pulses. With a suitably intense laser beam and proper target construction, it was proposed that economical laser-induced nuclear fusion was feasible.³⁻⁵ This was followed by an experimental demonstration of laser fusion at KMS Fusion Inc., Ann Arbor, MI,⁶ at LLL,⁷ and elsewhere.⁸

With the laser's invention in 1958,⁹ national programs began, which have supported its development to the present, relatively well-understood experimental state. Some highlights for *pulsed* laser development are given in Table I.

Much of the descriptive laser work presented here is based on laser science as developed in the 1960s. Excellent references to the work of this period are given in Refs. 10 and 11. Glass lasers specific for plasma and fusion applications were developed in the mid-to-late 1960s by the Compagnie General d'Electricite (Marcoussis, France), at the Lebedev Institute (Moscow, Russia), at Sandia Laboratories (Albuquerque, NM), and at the Lawrence Livermore Laboratory (Livermore, CA). The power levels of the first systems were modest, about 0.01 TW (1 TW = 10^{12} W). Since that time the technology of high-power, pulsed-laser systems has developed dramatically. Examples are the 20-TW Shiva system (Fig. 1) and the Helios 10-TW CO₂ laser. Now under construction are the Nova 300-TW glass laser and the Antares 100-TW CO₂ laser. Designs for more energetic lasers (~ 1 MJ) have been proposed, with overall efficiencies of $\sim 5\%$ and reliabilities of $> 10^7$ shots between major maintenance cycles. A good compilation of articles on lasers for plasma applications is given in Ref. 12. A compendium of the Livermore work is given in the Livermore Laser Program Annual Reports.¹³ An excellent review of advanced laser concepts is given in Ref. 14.

This report was organized to give the reader an outline of the basic laser and optical principles that are important in high-power laser design. Examples of successes and failures are drawn primarily from experiences at the Livermore Laser Program. It is hoped that by reading this report, the reader will gain enough information on fusion-laser design that when the reader contemplates building a laser system, or simply using one for experiments, the system's limitations and possibilities will be apparent.

FIG. 1. Twenty-beam Shiva Laser system provides more than 20 TW on a laser-fusion target in a 100 ps pulse.

TABLE 1. Pulsed laser developments.

Development	Investigators	Year
Invention	Schawlow and Townes	1958
First laser (Cr ³⁺ in Al ₂ O ₃)	Maiman	1960
He-Ne laser	Javan, Bennett, and Herriott	1961
Nd:glass laser	Snitzer	1961
Master oscillator-pulse amplifier	Kisliuk and Boyle	1961
Q-switching	Hellwarth	1961
Giant pulse ruby laser	McClung and Hellwarth	1962
CO ₂ laser	Patel	1964
Nd:YAG laser	Geusic, Marios, and van Uitert	1964
Iodine laser	Kasper and Pimentel	1964
Faraday rotator	Aplet and Carion	1964
Mode-locking	DiDomenico	1964
	Hargrove et al.	1964
	Yariv	1965
Self-focusing	Chiao, Garmire, and Townes	1965
Nd:glass fusion lasers	Ernest, Riffard, Robieux, and Sturel	1965/66
Disk laser amplifier	Almasi et al.	1966
	Swain et al.	1969
TEA lasers	Beaulieu	1969
	Dumanchin and Rocca-Serra	1969
Excimer laser	Basov	1970
Pulsed iodine laser	Holla and Komp	1972
E-beam/sustainer	Fenstermacher et al.	1971
	Daugherty et al.	1971
High-power spatial filtering	Glaze, Rainer, and Simmons	1975
KrF laser	Ewing and Brau	1976
Relay imaging	Hunt	1976
Shiva multi-beam Nd:glass laser	Emmett et al.	1977
Helios multi-beam CO ₂ laser	Boyer et al.	1978

LASER-TARGET SYSTEM

The laser-target interaction system consists of an oscillator, amplifiers, propagation devices, a target system, and diagnostics. The purpose of the laser-target system is to deposit sufficient energy in an appropriate time interval on interesting targets. In turn, the target experimenter measures target response as plasma temperature, material acceleration, x-ray production, and neutron production. To do this in a predictable fashion, or at least in a repeatable fashion, the laser input to the target must be well controlled, repeatable, and predictable. The experiment usually requires 10 J in 1 ns (10^{10} W) or greater in order to accomplish interesting physics. Although a great deal of interesting physics was accomplished with lasers of lower performance, modern laser-fusion-oriented experimentation is being carried out with devices exceeding this level. The present state of the art for laser systems is >100 kJ in 1 ns, or $>10^{14}$ W. In fact, systems such as Shiva at LLL are presently operating on target at $>2 \times 10^{13}$ W and Helios at Los Alamos Scientific Laboratory (LASL) is operating at $>2 \times 10^{12}$ W.

Figure 2 shows the components of a laser system. They are (1) the oscillator, which creates the seed pulse with the proper pulse shape; (2) the propagation path and telescope system, which projects and magnifies the beam as it leaves the oscillator and traverses the amplifiers and projects it to the alignment mirrors and focus lens; (3) the power amplifiers, which amplify the 0.1–1.0 mJ oscillator pulse to the desired level of 10^1 – 10^5 J; (4) the system stabilizing and isolating elements, which prevent target reflections from returning and damaging the laser system and prevent the amplifier from self-oscillating off the target or its own surfaces; (5) the mirror and focusing lens system, which directs the laser light down onto the target; (6) the target itself, which defines the beam focal requirements; and (7) the diagnostic systems, which are used to analyze the performance of the laser and to determine the interactions of the laser beam with the target.

Because laser oscillators must provide precisely controlled laser pulses, they are limited to 0.1–1.0 mJ of output energy. If the experiment requires 10^1 – 10^5 J on target, the system pulse gain will be at least 10^4 – 10^8 .

Because of losses and saturation effects, the required small-signal amplifier gain will be even larger (10^5 – 10^9). Laser amplifiers, which provide this gain in a well-controlled manner, come in convenient pulse-gain packages of 10–100× in small diameters and 2–10× in large diameters. Approximately 10 amplifiers in series are required to amplify the beam to reasonable levels. The diameter of the amplifier increases from approximately 1.0–50 cm in order to accommodate the ever-increasing energy in the beam, while not exceeding damaging fluences.

The propagation elements expand and control the beam shape in such a way that no damage is done to the laser components by the intense laser field. These elements prevent the beam from hitting aperture edges, provide correct diameter, etc., yet do this in such a fashion that they form the most spatially compact, lowest-cost laser chain. The isolator package is required to control both laser self-oscillation and target reflection because, with amplifier gains of $>10^4$ – 10^7 , even the smallest dirt speck or target glint will provide a reflectivity of 10^{-4} – 10^{-7} , thus causing the laser-oscillation condition to be satisfied. If this occurred, low-level fluorescence noise would be amplified to large levels, causing laser self-damage or target destruction. Under pulse conditions, targets routinely reflect 10–20% and sometimes more than 50%. Amplification of this reflected light back toward the laser, as the beam is “minified,” will inevitably lead to damage. Thus, isolation is mandatory.

The target system consists of the pointing mirrors, focusing lens, target manipulator, and diagnostic systems. This system’s primary purpose is to aim the laser beam (usually converging) onto a selected target area, typically 100 μm diam. At the same time the diagnostic system verifies the laser performance, i.e., it measures energy, pulse evolution, quality of focal distribution, and energy reflected back from the target into the focusing lens. (The measurement of laser light scattered in other directions will not be discussed here, although total laser-energy accounting is important because it is one of the few ways to accurately measure target absorption.) The most obvious part of this system is the focus lens, which concentrates the beam energy to the target. However, the focal quality of this system cannot overcome poor optical quality in the incoming laser beam. The focal quality is a function of beam aberrations caused by thermal loading, nonlinear focusing, material index gradients and beam-induced material breakdown.

For most target experiments, and with reasonably designed lasers, the best attainable laser focal-spot diameter is usually smaller than needed for the experiment. The experiment is often performed in the converging section of the beam at the appropriate radius as shown in Figs. 3 and 4.

FIG. 2. Components in laser-target interaction system.

FIG. 3. Irradiated target is often located in front of the best focus of the lens. Thus the experimenter controls power density and spot size. Focal-spot quality is a function of beam's amplitude and phase uniformity.

100 μm
Target

800 eV x-ray image

FIG. 4. Simple ball target (left) is irradiated by two converging laser beams; (right) x-ray image of the target implosion.¹³

TABLE 2. Orders of magnitude of measurements used in laser experiments.

Measurement	Order of magnitude
On-target energy	10^{-10} – 10^5 J
Pulse duration (shorter pulses, 5×10^{-12} s, are primarily of interest as diagnostic tools)	10^{-10} – 10^{-8} s (0.1–10 ns)
Average energy fluence (governed by breakdown thresholds and self-focusing)	2–20 J/cm ²
Typical beam intensities	10^9 – 10^{10} W/cm ²
Peak beam electric fields (for 10^9 – 10^{10} W/cm ²)	$1-3 \times 10^6$ V/cm
Peak beam magnetic fields	3000–9000 G
Beam wavelengths	0.25×10^{-4} – 10^{-3} cm (0.25 μ m–10 μ m)
Beam frequencies	3×10^{13} – 10^{15} Hz
Optical periods	3×10^{-14} – 10^{-15} s (0.03–0.001 ps)
Number of optical cycles in pulse of 1 ns	3×10^4 – 10^6
Beam diameters	5–50 cm
Intensity on target	10^{12} – 10^{16} W/cm ²
Strength of the E fields for the above focused spot	3×10^7 – 3×10^9 V/cm
B fields	10 k–10 MG
Typical time scales of interest	
Laser optical period	10^{-14} s
Fusion burn time	3×10^{-11} s (30 ps)
Laser pulse duration	10^{-9} s (1 ns)
Laser medium pumping time	10^{-7} – 10^{-3} s
Capacitor charging times	1– 10^2 s

ORDERS OF MAGNITUDE

Several numbers are used routinely in laser-plasma experimentation. They are summarized in Table 2.

LASERS

The laser described in Ref. 9 is a device that coherently amplifies optical radiation. (The acronym means Light Amplification by Stimulated Emission of Radiation.) The key observation leading to the demonstration of laser action was that certain nonthermal electron energy distributions could be created in materials, and under these conditions, the stimulated emission coefficient (the Einstein B coefficient) associated with the electron transition will cause an optical field to grow in strength rather than be attenuated. By suitably placing an optical resonator (mirrors) around the prepared medium, spontaneous fluorescence associated with the random de-excitation of the electron levels is collected by the surrounding mirrors (Fig. 5). It is redirected back and forth through the medium, and the optical field grows from the very low levels associated with spontaneous emissions to very high levels, which are usually limited by material breakdown.

FIG. 5. Laser oscillation occurs when fluorescence noise grows in intensity in cavity.

As an example, select a 1-cm-diam sphere from the laser rod in the cavity shown in Fig. 6. The rate of emission from the sphere of fluorescing material is approximated by dividing the instantaneous stored energy by the fluorescence decay time. For example, if we use a typical laser medium that stores 0.1 J/cm^3 and has a fluorescence decay time of $100 \mu\text{s}$, then

$$\frac{E}{t_f} = \frac{0.1 \text{ J/cm}^3 \times \text{vol.}}{100 \mu\text{s}} = 522 \text{ W}.$$

Thus 522 W are radiated into 4π sr of solid angle, through a surface area of 3.14 cm^2 . This leads to a $13\text{-W/cm}^2/\text{sr}$ fluorescence noise level.

This is now compared to the typical angular acceptance of a fusion target, which is $d\theta \approx 10^{-4} \text{ rad}$, or a solid-angle acceptance of $(d\theta)^2 = d\Omega = 10^{-8} \text{ sr}$. In addition, typical fluence limits for fusion lasers are $10^9\text{--}10^{10} \text{ W/cm}^2$. When beams of this fluence propagate within the $10^{-8}/\text{sr}$ acceptance angle, $10^{17}\text{--}10^{18} \text{ W/cm}^2/\text{sr}$ radiance levels must be achieved.

In Fig. 6 the noise level was $13 \text{ W/cm}^2/\text{sr}$. The gain required to go from $13 \text{ W/cm}^2/\text{sr}$ to $5 \times 10^{17} \text{ W/cm}^2/\text{sr}$ is 3.8×10^{16} . If "gain-equal-to-10" amplifier sections are used in the laser, approximately

FIG. 6. Laser radiance is determined by power/area/solid angle.

FIG. 7. Radiance amplification in laser system.

FIG. 8. Radiance amplification in cavity.

17 amplifiers are required to reach the required radiance levels (assuming no losses, aberrations, gain saturation, or area expansion). This is shown in Fig. 7.

The required radiance amplification can be performed in a very compact fashion (see Fig. 8) by placing mirrors around the gain medium and allowing the laser medium to both emit optical fluorescence noise to start the laser action, and to amplify the signal from the low-radiance levels of fluorescence noise to the high radiance required for target illumination. In other words, the oscillator cavity compactly amplifies the signal from noise to radiance levels limited by the beam-diameter-imposed diffraction limit, by propagation constraints or damage, and/or nonlinear self-focusing limits. Stages of amplification following the oscillator can increase both the radiance of the oscillator pulse and the total beam power by reducing the diffraction-limited angular divergence, by increasing the area of the beam, and by amplifying the beam's intensity to the damage limit at the exit aperture of the amplifier system. The radiance and total beam power are eventually increased to the limit permitted either by dielectric breakdown or by defocusing optical aberrations associated with the increasing size of the amplifier system. An example¹⁵ of laser-beam radiance is shown in Fig. 9.

Circle diam
23 μm

Shot #4, 9/30/76

FIG. 9. Focal spot of Argus laser system. Radiance in this example is $1.5 \times 10^{18} \text{ W/cm}^2/\text{sr}$.

LASER GAIN

The details of laser operation are given in several excellent books and papers (e.g., Refs. 16 and 17). The amplification of a laser beam in a lossless medium proceeds as described by the following equation

$$\frac{dI}{dz} = \alpha I,$$

where I is the laser energy fluence and α is the stimulated-emission coefficient, or the gain coefficient. This equation integrates to

$$I = I_0 \exp(\alpha z).$$

FIG. 10. Energy-level diagram for laser medium.

As long as α is independent of l , the laser-beam fluence will exponentially increase as it traverses the gain medium. However, α does decrease as l increases, because the laser inversion level is decreased as the front part of the optical pulse passes through the medium, leaving a lower gain for the rear part of the pulse.

The term $\alpha(\lambda)$ can be written as the sum of two parts, $\alpha(\lambda) = N\sigma(\lambda)$, where N is the inversion density in number per cm^3 of the lasing species and $\sigma(\lambda)$ is the gain per ion, or the stimulated cross section. The units for $[N] = \text{cm}^{-3}$ and for $[\sigma(\lambda)] = \text{cm}^2$.

A simple schematic of the optical transitions leading to laser gain is shown in Fig. 10.

Following notations in Ref. 17, the laser-gain coefficient at the center wavelength of the transition is:

$$\alpha(\lambda) = \left(N_i - \frac{g_i}{g_f} N_f \right) \lambda^4 f(\lambda) / 8\pi n^2 t_s c .$$

At the line center wavelength for a Lorentzian linewidth function, for example, pressure line broadening, the gain coefficient is

$$\alpha(\lambda) = \left(N_i - \frac{g_i}{g_f} N_f \right) \lambda^4 / (2\pi)^2 n^2 c t_s \Delta\lambda .$$

The terms in the gain equation, which vary with laser type, are as follows:

λ	The wavelength, which varies rapidly with laser species.
$1/t_s$	The spontaneous emission rate, which varies rapidly with the stimulated-emission matrix element. Short-wavelength lasers usually do not store energy as well as longer-wavelength lasers because their fluorescence lifetime is short and consequently their gain is high because t_s^{-1} is large.
$N = \left(N_j - \frac{g_j}{g_i} N_i \right)$	The inversion-number density, which corresponds to energy storage in the medium. It varies between 10–500 J/liter. The g 's are degeneracy values describing the detailed atomic transitions. The number N is varied by adjusting the pump rate. This number should be as large as possible to reduce the volume of laser amplifier media.
n	Index of refraction of the laser media.
$\Delta\lambda$	The laser line width, which varies strongly with the laser transition. Typical values are 300 cm^{-1} in Nd:glass to $<0.1 \text{ cm}^{-1}$ for low pressure CO_2 . This parameter can be controlled to an extent by varying the pressure in a gas medium or by choosing different solid host materials to affect the characteristic ion line width.
$f(\lambda)$	The normalized line-width function, $\int_{-\infty}^{\infty} f(\lambda) d\lambda = 1$, which measures the transition strength relative to the line peak as a function of λ .

As an example, consider a Nd:glass laser amplifier that stores $\sim 0.5 \text{ J/cm}^3$ in an inversion (between the $^4F_3/2 \rightarrow ^4I_{11/2}$ transition of Nd in laser glass). This corresponds to 3×10^{18} excitations cm^{-3} . For $\lambda_{\text{peak}} = 1.061 \text{ }\mu\text{m}$, $n = 1.56$, and $t_s = 359 \text{ }\mu\text{s}$ /branching ratio. The branching ratio is the fraction of total radiative probability associated with the single transition from $^4F_3/2 \rightarrow ^4I_{11/2}$; here it is 0.484. Putting these values into the gain equation above leads to a gain coefficient of $\sim 0.08 \text{ cm}^{-1}$ or 8%/cm. Examples of typical laser medium parameters are given in Table 3.

TABLE 3. Typical laser medium parameters.

Laser	$\lambda (\mu\text{m})$	$\alpha (\text{cm}^2)$	$N (\text{cm}^{-3})$	$\Delta\lambda (\text{cm}^{-1})$	$t_s (\text{s})$
Nd:glass	1.06	2.7×10^{-20}	3×10^{18}	340	360×10^{-6}
CO_2^a	10.6	6×10^{-19}	1×10^{18}	0.33	4.7
I_2	1.3	2×10^{-19}	1×10^{17}	0.56	0.13
KrF	0.249	2.5×10^{-16}	4×10^{14}	400	6.7×10^{-9}

^aP(20) line at 1800 Torr, 3:1/4:1, He:N₂:CO₂ mix.

LASER EXAMPLES

Figures 11–14 show laser parameters for four laser media, which are of primary interest to the fusion experimenter. They are Nd:glass,^{18–21} CO₂,^{22–24} iodine,^{25–29} and KrF.^{30–32}

FIG. 11. Properties of Nd:glass laser.

Spectroscopic properties of Nd:

Wavelength	1061 nm
Cross section	$2.7 \times 10^{-20} \text{ cm}^2$
Radiative lifetime	360 μs
Fluorescence line width	27.8 nm
Saturation fluence	5 J/cm ² .

Typical laser amplifier parameters:

Glass material,	Li-Ca-silicate
Amplifier diameter	34 cm
Pump source	Xe flashlamps
Flashlamp pump duration	600 μs
Pump energy	325 kJ
Small-signal gain	5 m ⁻¹
Efficiency (stored energy/pump energy)	2%
Stored energy in glass	0.35 J/cm ³ (350 J/liter).

FIG. 12. Properties of the CO₂ molecular laser.

Molecular properties:

Wavelength	10.6, 9.6 μm
Cross section	(P(20) 1800 Torr) $6 \times 10^{-19} \text{ cm}^2$
00^0_1 Radiative lifetime	4 ms
00^0_1 Collisional lifetime (laser mix)	$\sim 4 \mu\text{s}$
Saturation fluence (all rot levels)	0.2 J/cm^2

Typical laser parameters:

Gas mixture	He:N ₂ :CO ₂ , 1280:110:410 Torr
Operating E/N	$\sim 2 \times 10^{-16} \text{ V/cm}^2$
Applied field	$\sim 4 \text{ kV/cm atm}$
Pump current density	$\sim 10 \text{ A/cm}^2$
Pump duration	2–4 μs
Small-signal gain coefficient	0.05 cm^{-1}
Stored energy density	10–20 J/liter atm
Efficiency (short pulse)	2–10%

FIG. 13. Properties of the atomic iodine laser.

Atomic iodine properties:

Wavelength	1.312 μm
Cross section (laser mixture)	$2 \times 10^{-19} \text{ cm}^2$
Radiative lifetime	130 ms
Inversion lifetime	$\sim 10 \mu\text{s}$
Saturation fluence	0.5 J/cm^{-2}

Typical laser parameters:

Gas mixture	Ar: $\text{C}_3\text{F}_7\text{I}$ 1250:6 Torr
Pulse duration	10 μs
Lamp fill	Xe, 5 Torr
Small-signal gain coefficient	$\sim 0.02 \text{ cm}^{-1}$
Stored energy density	15 J/liter
Efficiency	$\leq 1\%$

FIG. 14. Properties of the E-beam pumped KrF excimer laser.

Molecular properties:

Wavelength	249 nm
Cross section	$\sim 2.5 \times 10^{-16} \text{ cm}^2$
Radiative lifetime	$\sim 6.7 \text{ ns}$
Fluorescence line width	400 cm^{-1}
Saturation fluence	3 mJ/cm^2
Saturation intensity	$\geq 1 \text{ MW/cm}^2$.

Formation kinetics:

Typical laser parameters:

Gas mixtures	Ar:Kr:F ₂ 712:46:2.3 Torr
Beam voltage	$\geq 200 \text{ keV}$
Beam current	$10\text{--}30 \text{ A/cm}^2$
Pulse duration	$0.1\text{--}1 \mu\text{s}$
Pump rate	$0.3\text{--}1.0 \text{ MW/cm}^3$
Small-signal gain	$0.01\text{--}0.1 \text{ cm}^{-1}$
Nonsaturation photoabsorption loss coefficient	$\gamma \sim 5 \times 10^{-3} \text{ cm}^{-1}$
Gain/loss ratio	$\alpha/\gamma \text{ } 10\text{--}20$
Nonsaturable photoabsorbers	F ⁻ , F ₂ , Ar ₂
Intrinsic efficiency	10%.

GAIN AND SATURATION

In a saturating laser amplifier³³⁻³⁵ where the phase-memory time of the ions is short compared to the pulse width, and the pumping and decay times are long compared to the pulse width, the beam intensity of a pulse traveling toward +z obeys

$$\frac{\partial I}{\partial z} + \frac{1}{v} \frac{\partial I}{\partial t} = (\alpha - \gamma)I, \quad (1)$$

where v is the velocity of light in the medium (assuming there is no dispersion), α is the gain coefficient caused by the inverted ions, and γ is a nonsaturating fixed loss. The gain coefficient obeys

$$\frac{d\alpha}{dt} = -\frac{\alpha I}{\theta_s}, \quad (2)$$

where θ_s is a proportionality constant. We can see what this constant θ_s means by integrating Eq. (2) to obtain

$$\alpha = \alpha_0 \exp\left(-\int \frac{I}{\theta_s} dt\right).$$

The beam fluence at any point (energy per unit area) is defined as

$$\vartheta(t) = \int_{-\infty}^t I(t') dt', \quad (3)$$

so that Eq. (3) becomes

$$\alpha = \alpha_0 e^{-\vartheta/\theta_s} \quad (4)$$

and we see that the fluence θ_s is that beam fluence which reduces the inverted population (and thus the gain coefficient) to 1/e of its initial value. θ_s is generally called the saturation fluence.

It is convenient to change coordinates to a set in which

$$z' = z$$

and

$$t' = t - z/v$$

so that propagation moves the pulse in z' but not in t' . We then have

$$\frac{dI}{dz'} = (\alpha - \gamma)I, \quad (5)$$

which is integrable in time for the lossless case ($\gamma = 0$) to

$$\frac{d\vartheta}{dz'} = \int \alpha I dt'.$$

or using Eq. (4) for α :

$$\begin{aligned} \frac{d\vartheta}{dz'} &= \int \alpha_0 e^{-\vartheta/\theta_s} I dt' \\ &= \int \alpha_0 e^{-\vartheta/\theta_s} d\vartheta \\ &= \alpha_0 \theta_s (1 - e^{-\vartheta/\theta_s}) \end{aligned} \quad (6)$$

$$\frac{d\vartheta}{dz'} = \frac{\alpha_0 \theta_s (e^{\vartheta/\theta_s} - 1)}{e^{\vartheta/\theta_s}}.$$

With the change of variable

$$u = e^{\theta/\theta_s} - 1 ,$$

we get from Eq. (6)

$$\frac{\frac{\theta_s}{u+1}}{du} = \frac{\alpha_0 \theta_s u}{u+1} dz' , \quad (7)$$

which is the same as

$$\frac{du}{u} = \alpha_0 dz' .$$

This integrates to

$$u = u_0 e^{\int \alpha_0 dz'} .$$

and if we recognize that

$$\exp \left(\int \alpha_0 dz' \right) = G$$

is the small-signal gain along the path of the pulse before saturation takes place, we arrive at the fundamental equation for saturated lossless gain

$$e^{\theta/\theta_s} - 1 = G (e^{\theta_0/\theta_s} - 1) ,$$

relating output fluence θ to input fluence θ_0 , saturation fluence θ_s , and small-signal gain G . This can be written as

$$\theta = \theta_s \ln [1 + G(e^{\theta_0/\theta_s} - 1)] . \quad (8)$$

In the case where the lower laser level drains rapidly compared to characteristic pulse time, the saturation fluence is³³

$$\theta_s = \frac{h\nu}{\sigma} , \quad (9)$$

where σ is the cross section of the transition, h is Planck's constant, and ν is the frequency of the transition. If relaxation of the lower level is blocked, we have (where $k = g_1/g_2$)

$$\theta_s = \frac{h\nu}{\sigma(1+k)} , \quad (10)$$

where k is the degeneracy ratio of the upper and lower levels. For a simple two-level system, $k = 1$ and the saturation fluence is half of the full-drain value. In the intermediate case where partial drain takes place, we cannot use the equations we started with. However, experience has shown that satisfactory results may be obtained by the use of an "equivalent saturation fluence," which depends on the pulse duration.

Note that we may differentiate the fluence growth equation to get the intensity gain as a function of time during the pulse as

$$I(t') = \frac{I_0(t')}{1 - e^{-\theta_0/\theta_s} (1 - 1/G)} , \quad (11)$$

where now θ_0 is the input fluence up to time t' in the pulse. This expression allows us to find the temporal distortion of saturated pulses. Some examples from Ref. 35 are shown in Figs. 15-18.

Up to this point we have ignored the effects of a fixed loss coefficient γ . Recalling that

$$\frac{dI}{dz'} = (\alpha - \gamma)I .$$

FIG. 15. Spatial and temporal shape of the initial pulse into a lossless saturating laser amplifier. The pulse is a spatial (front to back) and temporal (left to right) Gaussian with radial symmetry. (a) Front view; (b) rear view.

FIG. 16. Spatial and temporal shape of an initially Gaussian pulse in a lossless saturating laser amplifier. Energy density at center is 1 saturation fluence. (a) Front view; (b) rear view. (Time is left to right.)

FIG. 17. Spatial and temporal shape of an initially Gaussian pulse in a lossless saturating laser amplifier. Energy density at center is 5 saturation fluences. (a) Front view; (b) rear view. (Time is left to right.)

FIG. 18. Spatial and temporal shape of an initially Gaussian pulse in a lossless saturating laser amplifier. Energy density at center is 10 saturation fluences. (a) Front view; (b) rear view. (Time is left to right.)

we see that for low-level signals the small-signal gain changes from

$$G = \exp\left(\int \alpha dz'\right) \quad \text{to} \quad G = \exp\left(\int (\alpha - \gamma) dz'\right).$$

There must be enough inversion that $\alpha > \gamma$ or the amplifier will be an attenuator. Even this is not enough if the beam saturates the amplifier and reduces α below γ . Including loss, we have from Eq. (6):

$$\frac{d\theta}{dz'} = \alpha_0 \theta_s (1 - e^{-\theta/\theta_s}) - \gamma \theta, \quad (12)$$

so the fluence cannot rise above an equilibrium value given by

$$\frac{d\theta}{dz'} = 0 \quad \text{or} \quad e^{-\theta/\theta_s} = 1 - \frac{\gamma \theta}{\alpha_0 \theta_s}.$$

Some solutions (θ/θ_s) of this equation for various ratios of gain to loss are:

α_0/γ	1.1	1.2	1.5	2	5	10
θ/θ_s	0.1937	0.3764	0.8742	1.594	4.965	10

The conclusion is that the beam fluence (measured in saturation fluences) cannot exceed the ratio of gain to loss. The above analysis refers to laser pulses short compared to medium lifetimes. For laser pulses long compared to medium lifetimes, the equation in Fig. 19 holds. This observation is especially relevant to the KrF laser system where a nonsaturating loss is present, 0.005 cm^{-1} , and the saturation fluence is low, 0.003 J/cm^2 . Figure 19 shows an example of this problem.

FIG. 19. Nonsaturable losses in power amplifiers limit the maximum fluence to be $I_{\text{sat}} [(\alpha_0/\gamma) - 1]$.

FREQUENCY AND BANDWIDTH

The laser gain is a function of frequency as described previously. The line-width function $f(\lambda)$ is determined by the shape of the laser transition lines. The shape is determined by a variety of physical processes—Doppler and collision effects in gases; strain or lifetime in solids.

The resultant line width of the laser signal is influenced by this line shape, because it determines both the fluorescence noise spectrum and the gain spectrum. This fluorescence line as measured by the FWHM value is narrowed by the laser gain. This is a consequence of the large ($\sim 10^{17}$) gain required to develop the laser emittance from the spontaneous level to that of a fusion laser. As an example, consider a typical laser transition with a gain coefficient of 0.05 cm^{-1} ; that is, a small-signal gain $= e^{0.05L} \sim 10^{17}$.

The length of material traversed (both in a cavity and in the amplifier chain) would be about 780 cm to reach the gain of 10^{17} if the laser signal were at line center. Consider the gain at $(\lambda_0 - \delta)$ in Fig. 20, where $\alpha(\lambda_0 - \delta) = 0.9 \alpha_{\text{max}} = (0.045 \text{ cm}^{-1})$; then $e^{(0.045/780)} = 2 \times 10^{15}$, which is a factor of 50 lower than the gain at line peak. One finds that line widths are reduced by approximately $(\ln G)^{1/2}$ after a gain of G .

Figure 21 sketches the narrowing of the fluorescence line width as a consequence of the exponential gain process. If other frequency-selection elements are inserted in the oscillator cavity or in the amplifier chain, further spectral modification occurs. This is discussed later. Finally, while this example shows the results of exponential gain in the time domain, similar effects occur if amplifier gain is not uniform in space over the gain aperture. For example, a long series of rod amplifiers, each with small nonuniformities in gain vs radius, can cumulatively have a very nonuniform gain vs radius profile.

FIG. 20. Laser gain as a function of wavelength.

FIG. 21. Effective line narrowing caused by exponential gain. Line shape 3 is gain narrowed compared to initial line shape 1.

FOCUSABILITY

The increase in radiance between the oscillator and the focusing lenses, due to coherent gain through the amplifier, only occurs if the optical train does not degrade the phase front and reduce the power/sr. Such deterioration occurs when the gain medium (gas or solid) or the beam-handling optics distort the beam phase front. An example of an interferogram from an optic producing such a deterioration is shown in Fig. 22. Aberrations such as these cause parts of the laser beam to diverge from the main-beam direction, causing interference ripple in the near field and "lobes" of energy to move away from the focal spot in the far field.

A simple but instructive way of looking at aberrations is that if a wave is differentially retarded in phase by $n\lambda$ (n waves) over an aperture D , its focal position will be displaced by a distance $(n\lambda/D)f$. If only part of the wave front is unevenly retarded over a shorter distance d , the phase gradient is larger and energy will be "thrown" farther from the center of the focal spot (see Fig. 23).

A more rigorous way of looking at focusing^{36,37} is to consider the lens as a transformation element. Because lenses can be made almost theoretically perfect from $f/100$ to $f/0.4$, it is the laser optical quality, not the lens quality, that determines the amplitude and phase distribution of the focused beam as it converges toward the focal plane. The lens transforms (with t_{lens}) the incoming beam by imposing a phase envelope (usually spherically converging^{6,38}) onto the phase of initial beam.

$$E'(x,y) = t_{\text{lens}}(x,y) \cdot E(x,y) ,$$

FIG. 22. Interferogram of a lens producing degraded phase front. The curvature of the lines shows that about $\lambda/2$ of phase aberration over the aperture will be imposed on a laser beam by this optical element.

where $E(x,y)$ is the complex optical field immediately preceding the lens, E' is the field immediately following the lens, and $t_{\text{lens}}(x,y)$ is the lens transformation function. For paraxial rays

$$t_{\text{lens}}(x,y) = \underbrace{\exp(jkn\Delta)}_{(1)} \exp\left(\underbrace{-j\frac{k}{2f}r^2}_{(2)}\right) \quad ,$$

where k is the wave number $2\pi/\lambda$, n the index of refraction, Δ the lens thickness, f the lens focal length, and r the distance from the beam axis to the measuring point. Term (1) is simply an overall phase delay of $n\Delta$, and term (2) shows that there is phase curvature $k(r^2/2f)$. Visually, a picture of focusing is obtained as shown in Fig. 24. As the beam proceeds toward the focal point, the phase information is converted to amplitude intensity and, when the beam reaches the focal plane, the phase information and amplitude information are displayed such that the intensity distribution vs (x,y) at the focal plane is the power spectrum of the beam at the lens aperture: that is, the lens *Fourier transforms* the beam.³⁶

The Fourier-transform view of focusing yields some interesting effects, e.g., a spatial Gaussian beam envelope focuses to a Gaussian distribution at the focus, since the Fourier transform of a Gaussian is a Gaussian (see Ref. 16 for a complete description of Gaussian laser-beam focusing). A narrow (positive or negative) intensity spike, such as a δ function or the shadow behind a dirt spot, focuses over a very broad area (see Fig. 25). This observation leads to the concept of spatial filtering.

FIG. 23. Phase aberrations steer the focal spot of the laser beam. Notice that it is the beam area affected by the gradient that determines the degree of focal deterioration.

A zero-phase aberration beam, apertured by the lens holder, focuses to a spot that is described by the Fourier transform of a round disk or the Airy pattern (e.g., see Fig. 26).³⁹

The diameter d_f of the focal spot to the first zero for a circularly apertured plane wave, with diameter D and focal length f is:

$$d_f = 2.4 \frac{\lambda}{D} f.$$

This is the best focal spot possible for a circular beam of uniform phase and amplitude. For example, at $\lambda = 1 \mu\text{m}$ and $f/D = 5$, the spot size $\approx 12 \mu\text{m}$. For usual fusion-laser systems, depending on the laser wavelength and the lens f/D (f number), focal spots are obtained from $1 \mu\text{m} < \text{focus-diameter} < 100 \mu\text{m}$. If aberrations are present (Fig. 27) the focal spot is enlarged in proportion to the degree of the aberration.

In the introduction it was stated that the focal properties of most fusion lasers were sufficiently good that targets were usually irradiated in the converging beam. In this section the beam distribution at best focus was discussed because it is the limit to irradiation intensity and most importantly it is a useful diagnostic for detecting laser optical aberrations. The actual laser intensity distribution in the intermediate converging regime, between the laser-output beam profile and the best-focus profile, is determined experimentally or with simulation codes.⁴⁰

FIG. 24. Phase fronts are transformed by the lens to the Fourier power spectrum at the focus.

FIG. 25. (a) Pinhole truncating the focal pattern (Fourier transform) of incoming beam pattern at a position that leads to a rippled reconstructed beam. (b) Intensity spike is focused broadly at the pinhole while the beam-envelope transform passes through the pinhole. (c) Periodic ripple on a beam focuses outside the pinhole aperture, allowing a smooth beam profile to be reconstructed. Note that the pinhole is $\sim 10\times$ larger than the diffraction limit of the main beam.

FIG. 26. Intensity distribution function for aberration-free circular pupil.

FIG. 27. Intensity distribution function for five wavelengths of third-order coma.

LASER OPERATIONAL CONSTRAINTS

An oscillator and gain elements must be assembled so as to obtain a controllable, non-self-destructing laser for experimentation. In this section the limitations imposed on gain media, by considerations of parasitic oscillation, amplified spontaneous emission, and chain self-oscillation, will be described. The additional limitations on the propagation of intense beams of light through laser components will also be described. These limitations arise because of linear losses, dielectric breakdown, self-focusing instabilities, intensity-dependent losses, and coherent intensification.

GAIN CONSTRAINTS

Amplifier gain is required to bring a pulse from the oscillator (~ 0.1 – 1 mJ) to the desired full amplifier output $\sim 10^3$ – 10^4 J. This requires a gain of $\sim 10^6$. Additional small-signal gain is required to overcome fixed losses and saturation. A single amplifier possessing a gain of 10^6 would not be stable. If there were a reflectivity of only 10^{-6} (an unobtainably small value), this amplifier would break into uncontrolled internal oscillation, since the laser gain condition $GR > 1$ would be satisfied. The division of the total gain into controllable sections (amplifiers) is clearly necessary (Fig. 28). An isolation element such as a Pockels cell or Faraday rotator is placed between each amplifier segment.

CHAIN STABILITY

For an amplifier section to be absolutely stable, noise generated in the gain element must not grow to undesirable levels. $R_1 R_2 G^2$ must be less than 1. Values for typical reflectivities are given in Table 4.

An example of an oscillating laser element is shown in Fig. 29. Very high gain at the edge of a non-uniformly pumped rod causes oscillation to occur between the edges of metal apertures.

Conditional stability can sometimes be achieved by having the gain G turned on in a short time period, as compared to the oscillation growth time associated with distance l and reflectivities R_1 and R_2 .

The intensity in the stage in Fig. 28 will grow from spontaneously emitted photons or from noise leaking through from a previous stage according to:

$$I = I_0 (G^2 R_1 R_2)^{t/(2\ell/c)}$$

$$= I_0 \exp \left[\frac{c t}{2\ell} \ln(G^2 R_1 R_2) \right] :$$

FIG. 28. Isolation of laser chain by isolators I_1 and I_2 having reflectivities of R_1 and R_2 , respectively (neglecting reflections from other surfaces in the chain). Linear distance between two isolation elements is l , and G is the gain at the time when the stability condition is examined.

TABLE 4. Typical reflectivities of optical elements.

Optical element	Reflectivity
Uncoated glass-plate surface	0.04
AR-coated glass plate	0.001
Metal edge	0.5
Uniformly scattering damage or dust speck, 1 mm diam, backreflecting into 10^{-3} sr	0.001 ^a

^aOver its obscuration area neglecting diffraction.

thus the e-folding time is

$$\tau_e = \frac{2\ell/c}{\ln(G^2 R_1 R_2)}$$

Example: $G = 20$, $R_1 = 0.01$, $R_2 = 1.0$ (in Fig. 28 assume that I_1 is absent and the target reflects 100%), and $\ell = 10$ m. Thus, $\tau_e = 4.8 \times 10^{-8}$ s and 10 e-folding times (for a gain of 2.2×10^4) occur in 480 ns.

Very rapid gain switching must occur for this technique to be useful for isolation. This conditional stabilization is useful for amplifiers that can be pumped very rapidly (~ 400 ns), such as KrF, and for amplifiers that are located a long distance from the target, for example the Antares CO₂ laser system at Los Alamos. For Nd:glass (pump ~ 0.5 ms) this technique is not useful as an isolation method.

Parasitic oscillation at edge of α -rod ($G > 200$)

FIG. 29. Parasitic modes oscillating near edge of laser rod, where the nonuniform gain in this rod amplifier is highest.

TARGET ISOLATION

Isolation from target reflection is required for both low- and high-power conditions. At very low power, a target placed exactly at best focus can serve as an almost perfect retroreflector, $R_T \sim 100\%$ (Fig. 28). At high power targets typically reflect 10–20% of the incident radiation directly back into the acceptance angle of the laser, and up to 70% back reflections have been observed under special target conditions. In addition, it is undesirable to place a passive isolator, such as a Faraday rotator, between the last gain element and the target (I_1 in Fig. 28), because of its losses and damage problems. This situation imposes a more stringent constraint on the output gain section. The condition $R_2 R_T G^2 < 1$ must be satisfied, where $R_T \sim 1.0$ and R_2 is constrained by realistic reflectivities (see Table 4). For $G \sim 10$, $R_T \sim 50$ – 100% , R_2 must be $\sim 1\%$, a value that requires some attention to achieve. A parasitic mode can easily develop in an amplifier chain (especially a chain with no spatial filter restricting the mode propagation angles) by scattering from the target at one end and the high reflectivity of a metal lens holder, screw head, or even a damage spot on a coating. The oscillation can rapidly develop to a level that destroys the target.

High-power isolation from target retroreflection will be required in the laser-output gain section because eventually $I_{\text{refl}} G_T > I_{\text{damage}}$. In this case the gain for the reflected pulse G_r will usually be lower than the small-signal gain because the forward propagating pulse has reduced the laser inversion level. By proper design an isolator at I_2 in Fig. 28 will suffice, or one can use a fast-closing pinhole isolator, such as a plasma device,^{41–43} or, in special circumstances, add an output isolator stage I_1 and accept the limitations of its additional nonlinear phase contributions and lower damage threshold.

An example of isolation, the Shiva laser isolator scheme,⁴⁴ is shown in Fig. 30. In this example the propagation is traced in the backward direction for both polarizations. This is required because of the polarization sensitivity of disk amplifiers and Faraday rotators. The Faraday rotators are noted as FR and the Pockels cells as PC.

TRANSVERSE OSCILLATIONS

In the previous sections, the stability requirements for isolating amplifiers from each other and from the target were discussed. Similar considerations occur within the individual amplifier.^{45–47} The stored gain within the amplifier is such that if internal reflectivity is not controlled, the amplifier will break into oscillation internally and the gain level will be clamped at the oscillator threshold condition inside the disk, $G^2 R_1 R_2 \leq 1$. Examples of modes are shown in Fig. 31 and gain clamping is shown in Fig. 32.

Figure 32 shows examples of the onset of parasitic modes that “clamp” the gain at an undesirably low level in a laser-disk amplifier.⁴⁸ In the two lower curves the edge reflectivity of the laser disks was not low enough to prevent the onset of internal oscillations.

AMPLIFIED SPONTANEOUS EMISSION (ASE)

In most laser systems, the amplifiers are excited before the laser pulse passes through and is amplified. During this “quiescent” time, spontaneous emission from the early amplifier stages can be amplified to levels that may damage the laser target. The amplified spontaneous emission develops along with the amplifier gain. In Nd:glass systems⁴⁹ it occurs over the 600- μ s flashlamp pump pulse, in CO₂ over the ~ 5 μ s sustainer pulse, and in KrF over the E-beam pulse period of ~ 100 – 500 ns.

Figure 33 is an example of fluorescence emission from a volume of Nd: laser material being amplified by subsequent amplifier stages. The geometry is similar to that shown in Figs. 6 and 7.

The energy reaching the target is $13 \text{ W/cm}^2/\text{sr} \times \frac{1}{4}\pi(5 \text{ cm})^2 \times 10^{-8} \text{ sr} \times 10^{-3} \text{ s} \times 10^6 \text{ gain} = 2.6 \text{ mJ}$. (Spectral line narrowing described earlier reduces this value by about four.)

This energy may be sufficient to damage fragile targets being used for experiments. The emission can be controlled by breaking up the amplifier gain path with fast-opening isolators such as Pockels cells or rotating shutters. Note that spatial filters reduce the ASE reaching the target.

FIG. 30. Isolation of Shiva laser with gains and damage thresholds appropriate for 100 ps pulse propagation. Note how the S reflection (cross polarization) grows in intensity as it propagates backward from the γ disk to the β disk. CR and VCR are isolation ratios.

FIG. 31. Internal parasitic modes within laser amplifier structure.

FIG. 32. Stored energy (gain) in 6.4-cm-diam disk laser amplifier as a function of flashlamp energy and disk edge preparation. Note the very low gains that occur when the edge reflectivities are high.

Figure 34 shows the ASE signal measured from a Shiva Nd:glass laser chain.⁵⁰ In Shiva, the small-signal gain after the noise-generating element is $\sim 10^5$, not 10^6 as in Fig. 33. Thus the integrated gain under the curve following the flashlamp pumping is acceptably low. However, when the early stage isolation Pockels cells open, additional noise from an earlier part of the chain shows up as a short intense noise pulse.

Amplified spontaneous emission also occurs within an individual laser amplifier and appears as a loss of stored inversion. When the gain coefficient-length product approaches five, $\alpha L \sim 5$, the loss of inversion caused by amplified spontaneous emission exceeds the natural fluorescence loss of the laser medium.⁴⁵ As a result, the excitation of high-gain amplifier media must occur at a rate significantly more rapid than the rate determined by the fluorescence time scale. For example, Nd:glass laser disks are most efficiently flashlamp pumped on the time scale of the fluorescence (spontaneous emission); thus amplified fluorescence is an important de-excitation mechanism.

FIG. 33. Amplified spontaneous emission generated in early chain stages.

FIG. 34. Shiva amplified spontaneous emission (ASE) on target from a single arm. Measured with 30 TW–100 ps laser settings.

LOSSES

As the laser beam travels down the amplifier chain, it experiences net gain and increases in intensity. However, the net gain is the difference between the laser medium gain and the inevitable losses. These losses arise from several sources. The major losses occur from Fresnel reflection from dielectric interfaces and passive losses in amplifier media or optical components. Loss of beam energy is undesirable because it is costly to recoup. In a 10-kJ laser beam, a 0.1% loss costs 10 J per occurrence and a 7% Fresnel loss costs 700 J, a loss greater than many small research lasers produce. Loss is especially severe in a saturated gain situation, where the beam gains energy slowly by extracting energy in proportion to the linear passage through the media, but loses energy at loss elements in proportion to the *total* beam fluence. Table 5 lists some linear losses in optical materials.

Additional low-level losses occur in laser systems, and these losses are not easily quantified. They are usually associated with clipping of the beam on an aperture, with dirty optics, with losses at the spatial-filter pinholes, etc. Gain reserve is required in a laser to overcome these losses.

NONLINEAR OPTICS

At power densities of 10^9 – 10^{10} W/cm², nonlinear optical processes begin to occur as the laser beam passes through the system optics. Coherent and sequential multiphoton effects occur because the laser dielectric media respond nonlinearly to the very intense laser beam. These phenomena are both detrimental and

TABLE 5. Linear losses in some optical materials.

Material	Linear loss
Laser glass	$\sim 0.002 \text{ cm}^{-1}$ bulk loss ^{21,51-53} < 0.001 surface loss ^{58,59}
Optical glass BK-7	0.002 cm^{-1} bulk loss ⁵⁴⁻⁵⁶ < 0.001 surface loss ^{58,59}
Faraday rotator glass	0.005 cm^{-1} ⁵⁷
AR coating	$0.001/\text{surface}$ ⁶⁰
100% turning mirror	$< 0.001/\text{surface}$ ⁶⁰ ($\sim 5\%$ loss if mirror is partially transparent for diagnostics)
Active CO ₂ laser gas mixture	0.0017 cm^{-1} ⁶¹
NaCl lenses	0.001 cm^{-1} ^{61,62}
AR coating on NaCl	$0.001/\text{surface}$ ⁶⁰
Germanium polarizer	0.015 cm^{-1} ^{61,62}

TABLE 6. Nonlinear phenomena in laser materials at 10^9 W/cm^2 .

Phenomenon	$\lambda (0.25 \text{ } \mu\text{m})$	$\lambda (1 \text{ } \mu\text{m})$
Two-photon absorption ^{63,64}	0.05 cm^{-1} loss coefficient in fused silica.	$< 0.01 \text{ cm}^{-1}$ in laser glass $< 0.001 \text{ cm}^{-1}$ in silica
Self-focusing and beam breakup ⁶⁵⁻⁷⁰	e^{28} growth/m in fused silica	$e^{3.4}$ growth/m in silicate laser glass
Whole-beam phase retardation ⁷¹⁻⁷³	$2.27 \text{ } \lambda/\text{m}$ path length of fused silica	$0.27 \text{ } \lambda/\text{m}$ of silicate laser glass
Stimulated Raman conversion ⁷⁴ (vibrational)	—	0.01 cm^{-1} gain coefficient in N ₂ at 1 atm
Stimulated rotational Raman ⁷⁵	—	2 cm^{-1} gain coefficient in H ₂ at 1 atm
2ω harmonic conversion ⁷⁶	—	$> 50\%$ energy conversion in 1 cm KDP

useful. A list of processes relevant to high-power laser operations is shown in Table 6. While most of these phenomena have been extensively studied with small ($\sim 0.1\text{-cm}$ diam) laser beams interacting over $\sim 1\text{-cm}$ interaction dimensions, the high-power laser designer must be concerned with large-scale manifestations of these phenomena over $\geq 10\text{-cm}$ beam diam and $> 100\text{-cm}$ interaction lengths.

These phenomena are listed first because of their crucial importance in determining the propagation limits in laser design, and second because of their potential usefulness in increasing the flexibility of presently available systems.

SELF-FOCUSING

Small-scale self-focusing is the major propagation limit for short-pulse laser systems.⁷⁷ Self-focusing occurs because the index of refraction of the dielectric optical material is equal to a field-independent term n_0 plus a field-dependent term $n_2 E^2$.

TABLE 7. Nonlinear phase retardation.

Material	$\gamma(\text{m}^2/\text{W}$ at $1.06\ \mu\text{m}$)	$\gamma(\text{m}^2/\text{W}$ estimated at $0.25\ \mu\text{m}$)
Silicate laser glass (ED-2)	3.8×10^{-20}	—
Fluorophosphate laser glass (E-181)	1.5×10^{-20}	—
Optical glass BK-7	3.4×10^{-20}	—
Fused silica	2.7×10^{-20}	8×10^{-20}

Thus

$$n = n_0 + n_2 \langle E^2 \rangle ,$$

or, rewritten in terms of the beam intensity,

$$n = n_0 + \gamma I .$$

Typical values^{21,73} for γ are given in Table 7.

At an intensity of $10^{10}\ \text{W}/\text{cm}^2$, the term γI for silicate laser glass⁵³ is 3.8×10^{-6} . A beam at this propagation intensity passing through 1 m of this glass will experience a phase retardation of $3.6 \times 10^{-6}\ \text{m}$, or 3.6 waves at $1\ \mu\text{m}$. A uniform phase retardation of this nature is not particularly serious, although it does lead to time-dependent beam aberrations.^{72,78} However, this effect leads to a serious propagation instability known as "small-scale" self-focusing. Growth of small-scale low-level beam ripples occurs because the nonlinear interaction causes power to transfer from the main-beam mode to the smaller-scale ripple modes via a parametric interaction.⁶⁵ Figure 35 schematically demonstrates the effect. Figure 36 shows the results of an experiment⁶⁸ showing this effect.

In a real laser system the major sources of the low-level ripples are diffraction ripples caused by dust particles, damage centers, clipped apertures, or interference fringes from incompletely coated optics or spatial filtering. The fastest-growing ripples (~ 0.5 – $1\ \text{mm}$ wide) will grow in relative intensity (when viewed at the focus of a lens where both phase and amplitude aberrations appear) as given by⁷⁹:

$$N = N_0 \exp(2B) . \quad (13)$$

FIG. 35. A small-amplitude (or phase) perturbation can grow in intensity at the expense of the main beam intensity until damaging levels are reached or until the total beam has filamented and become unfocusable.

where

$$B = \frac{2\pi}{\lambda_{\text{vac}}} \int_0^L \gamma I \, dz, \quad (14)$$

and

- N = noise amplitude relative to N_0 ,
- N_0 = initial noise amplitude,
- λ_{vac} = laser wavelength in vacuum,
- γ = nonlinear phase retardation coefficient (m^2/W),
- I = beam intensity in the optical material, and
- L = length of optical material through which beam travels.

Experimentally it has been found that values of $B \approx 3-5$ (depending on cleanliness and relay optics) are a propagation limit.^{15,77} Thus, $e^{2B} \approx 400$ and, if ripple growth does not exceed 100% beam amplitude (i.e., when $N = 1$), the initial noise N_0 must be 1/400 or 0.0025 of the main-beam envelope amplitude. It is also important to note that B is simply the beam-phase retardation in radians.⁷² $B = 3.14$ is equivalent to a $\lambda/2$ nonlinear phase retardation.

The intensification caused by self-focusing instability is of great concern to the laser designer and must be controlled. Lack of control reduces focusability by converting the high-radiance main-beam envelope

Spatial freq = 2/mm

$I_{\text{peak}} \approx 5 \text{ GW/cm}^2$

Gain $\approx 7\% \text{ cm}^{-1}$

FIG. 36. A purposefully modulated beam was propagated through a 24-cm rod of amplifier glass. The near-field ripple intensity was seen to grow exponentially.

FIG. 37. High spatial frequencies have divergent focusing angles which do not pass through the pinhole.

into fine nonfocusable filaments and causes laser damage where the intense filaments exceed damage thresholds. In order to maintain $B \gtrsim 4$, the laser chain must be divided into subsections where the ripple intensification can be reduced by spatial filtering^{80,81} (see Figs. 37 and 38). That is, the noise level N must be reduced to a manageable level N_0 whenever $B \rightarrow 4$ in the laser system. High-frequency spatial noise is reduced by spatial filtering with a lens and pinhole combination. An example of this technique applied to a 9-cm laser beam is shown Fig. 38.

FIG. 38. Reduction of high-frequency spatial noise by a lens and pinhole combination as applied to a 9-cm laser beam.

In system design the laser parameters in Eq. (14), such as beam intensity, glass path length, and material γ are manipulated. This manipulation is to *minimize* system cost while *maximizing* performance, and will be discussed in the last section of this report. The goal of the laser designer is to attain maximum performance from each laser-chain stage within the constraint of $B \leq 4$ between spatial filter segments, and a total nonlinear phase-retardation constraint of $\sum B_i \sim 10\text{--}12$.

DAMAGE LIMITS

The ultimate determination of a laser system's output aperture is the beam intensity that can be transmitted through a given aperture. Thus, a 10 kJ laser built with a 1 J/cm^2 damage constraint requires 10^4 cm^2 of output aperture (113 cm diam), whereas at 10 J/cm^2 only 10^3 cm^2 (36 cm diam) is required. Since the cost of a laser increases approximately in proportion to the total aperture *area*, the goal is to operate as close to the maximum-permissible propagation values as possible. Material selection has a profound influence on laser design because variations of 2–10 $\times$ in propagation limits can occur.

The phenomena that limit the laser-fluence intensity vary with laser wavelength, material, and beam intensity. In the long-pulse regime (where the long-pulse region is defined as not inducing nonlinear optical effects) the propagation limits are set by dielectric breakdown, which occurs most often on surfaces or on thin-film coatings on surfaces^{82,83} (see Fig. 39).

FIG. 39. Example of optical damage on an antireflection (AR) coating.

In this regime damage mechanisms are primarily associated with the heating of absorbing impurities until local material destruction begins. Then massive absorption of beam energy occurs and the material is permanently altered over an area larger than the initial breakdown site. The actual initiation of the material breakdown is the subject of a great deal of research and controversy. Figure 40 shows the progressive development of a damage site on a thin-film coating.⁸⁴ The damage appears to begin at the interface layer between the substrate and the coating layers, as evidenced by the lifting of the outer layers in (b). The damage begins at a localized site and then spreads, resulting in a completely damaged optic as shown in (c). A great deal of effort has been expended to raise the thresholds for damage, with some success.⁸⁵

Typical damage levels for both surfaces and material "bulk" are shown in Tables 8 and 9. Bulk-material damage thresholds are strongly affected by the presence or absence of inclusions.⁸⁶ Absorbing inclusions in glass can lower the damage threshold to $<5 \text{ J/cm}^2$; however, commercial laser-glass formulations by definition are free from these problems.

While the lists in Tables 8 and 9 are incomplete, they should give the reader a feeling for the variability in coating-damage thresholds as a function of production method and wavelength regime. To design a complex multicomponent laser system, operating fluence levels must be selected that are safely below commercially available component-damage levels measured at the desired pulse duration of the laser system.

The above discussions centered on damage limits without nonlinear effects. In the short-pulse operating regime, the short-pulse propagation limit is imposed by the accumulation of nonlinear-beam aberrations as discussed previously. The result of the nonlinear aberrations is either to make the beam unfocusable or to raise local beam ripples to the damage level of the optical system, before the average fluence of the laser beam reaches a desirable level. In the case where the constraint is actual surface damage, the mechanism for material breakdown with short pulses may be different from that for long pulses.^{89,90}

TABLE 8. Typical 1-ns single-shot damage thresholds.⁸⁷ The first value given in a two-value number (e.g., 5–15 J) is for production coatings, the second is for research one-of-a-kind coatings.

	0.25 $\mu\text{m}^{\text{a,b}}$	1.0 μm	10 μm
Optical surface			
Quartz (quartz film at 22 ns)	3,8	15–20	N ^c
NaCl (NaF film at 22 ns)	1,11	15	7
BK-7	3	15–20	N ^c
Antireflection coated surface	1	5–12	6
100% reflector surface	1,3	8–12	14
Bulk material damage			
Quartz	—	40	N ^c
BK-7	N ^c	40	N ^c
Laser glass	N ^c	40	N ^c
NaCl	—	—	10
Ge	5	N ^c	0.2 ^b

^aFirst value at 0.1-ns pulse, second value at 22 ns.

^bTransmission loss caused by plasma formation, actual damage not observed.

^cNot transparent.

TABLE 9. Damage levels in J/cm^2 of materials as a function of pulse duration for 1 μm laser light.⁸⁸

	0.1 ns	1.0 ns	3 ns	20–30 ns
Optical glass surface	7	15	25	100 J/cm^2
AR coating	4	5	6	20–40
100% reflector	6	8	10	16–50
Bulk glass level	—	40	—	100

FIG. 40. Damage morphology of four-layer Shiva AR coating (TiO_2 against substrate, then SiO_2 , TiO_2 , and SiO_2). The scale bar is $1.0 \mu\text{m}$ long. (a) The area indicated by the arrow shows incipient spall of surface-coating layers. (b) Surface layers lifting from substrate. (c) Thin-film layers removed and melted residue on substrate.

LINEAR PHASE-ABERRATION CONSTRAINTS

An additional constraint on propagation is the accumulation of *linear* phase aberrations. As mentioned earlier, with present fusion systems these have not yet been a serious limitation. However, as reactor laser designs are contemplated,⁹¹ the quality of the beam phase front is critical to the achievement of long stand-off distances and precise focusing. In gaseous lasers, the ultimate limitations to beam focal quality are the density fluctuations in the medium, $\Delta\rho/\rho$.⁹² In solid lasers, the cumulative polishing errors and material homogeneity set the aberration level. In addition, fluctuations in the air path between the laser and the target can also cause severe beam aberrations. Techniques to analyze cumulative aberrations for fusion applications are based on work by Vlasov et al.⁹³ and are briefly discussed by Haas and Glass.⁹⁴

APERTURE SIZE, FILL FACTORS, AND INTENSIFICATION

Several physical processes have been discussed that ultimately determine laser-system performance. One of the most important is the optical-component damage levels. The actual determination of permissible laser-operating fluence levels ultimately decides the laser output fluence.⁹⁵ Thus, a great deal of effort has been expended in maximizing the fluence-per-unit-area in a given laser system. In addition, one maximizes the *average* fluence through a given aperture by working to develop a smooth ripple-free beam. However, as has been seen, diffraction effects and small-scale self-focusing raise the peak beam fluence above the average beam fluence. A perfect system and a real system are shown in Fig. 41.

In Fig. 41(b), the average fluence (or usage of the output aperture at the amplifier exit) is reduced because of the following arguments. The beam intensity at $r = R_0$ (aperture edge) must be equal to zero, otherwise diffraction ripples from the aperture edge will propagate into the beam center. This causes a reduction in $2\pi\int f(r)rdr$ from $\pi R_0^2 f_{\text{max}}$ to $fR_0^2 f_{\text{max}}$, where f is the fill factor, or fraction of fill compared to a "square" beam. The radial shaping of light beams to enhance their focal or propagation properties is called "apodization." By using relay imaging techniques, little radial beam shaping is required compared to previous efforts. References to beam apodization efforts are given in Refs. 96–98. The best fill factor that can presently be obtained by using image relaying⁹⁹ is $f \sim 0.8$. Even with perfect relaying, diffraction from dirt, from inadvertent "edge clipping," or from self-focusing intensification, raises intensity peaks above the average main-beam intensity. Since permissible fluence is determined by *peak* fluence, the average beam energy must be somewhat less than $f\pi R_0^2 f_{\text{damage}}$.

FIG. 41. Apertures limit beam shape and nonuniform beam amplitude vs radius reduces fill factor.

FIG. 42. Improvement in beam quality of Argus laser at the 2.5 TW per beam intensity level.

Typical beam photographs taken on the Argus laser¹⁰⁰ are shown in Fig. 42. They demonstrate the improvements that have occurred on this system as beam fill factor was improved by reducing noise sources and sharpening the edges. In Fig. 42 it is apparent that the peak-to-average fluence margin has been reduced from >4 to 1 down to 1.3 to 1. However, if damage sites occur or beam misalignment occurs with consequent "edge-clipping," >2-to-1 beam modulation would reappear and damage would thus occur if the system was designed to operate at 1.3-to-1 modulation levels. A system designed to operate at 1.3-to-1 modulation levels requires careful maintenance, but the performance benefit is very high because the aperture is used very effectively.

COHERENT INTERFERENCE

Sources of modulation other than those described previously are associated with coherent reflections from surfaces, particularly on lenses, although tilted polarizer plates, beam splitters or diagnostic plates, and windows can cause reflections that coherently interfere and lead to intense standing waves and optical damage.^[6] The source of these intense standing waves is the coherent addition of electric fields from forward and reflected or scattered waves.

If the fields at point p in Fig. 43 are coherently added (assuming only two interacting fields) large modulations occur when the reflected wave adds in-phase or out-of-phase.

$$I(p) \simeq (E_1 \pm E_2)^2 = E_1^2 \pm 2E_1 E_2 + E_2^2, \text{ assuming } E_1 \gg E_2 \simeq E_1^2 \left[1 \pm 2(E_2/E_1) \right].$$

Thus

$$I(p) = I_1 \left[1 \pm 2(I_2/I_1)^{1/2} \right].$$

Example: If a secondary reflection $I_2 \simeq 0.01 I_1$ (1% of I_{incident}),

$$(I_2/I_1)^{1/2} \simeq 0.1,$$

then

$$I(p) = I_1 (1 \pm 0.2), \text{ a 20% modulation.}$$

FIG. 43. At point p a reflection from an uncoated surface is interfering with an incoming wave I_2 . This drawing assumes no reflection from the front surface, otherwise the coherent interference of three waves must be considered.

FIG. 44. Ghost-focus analysis. The incoming ray pair partially reflects from several surfaces until they cross at a "caustic" where the intensity can be great enough to cause damage.

FIG. 45. Lens on left (f/1) shows ghost-focus damage caused by off-axis caustics near center hole. Image on right is expanded view of damage around hole. Proper lens design is important to avoid problems for both forward-propagating laser beam and backward-propagating reflected beam from target.

Such modulation often occurs in diagnostic beam photographs if care is not taken to AR coat all beamsplitter surfaces. Similar effects can occur in optics within the laser chain.

In addition to the coherent effects, secondary reflections from laser components also can focus to cause both on-axis and off-axis "caustics," leading to system damage. These are called "ghost" foci and can occur in the lens or in another part of the laser system where the focal point occurs.¹⁰² Figure 44 shows a sketch of the intensification process. On-axis caustics inevitably occur, but are eliminated by boring a hole in the lens as shown in Fig. 45.

LASER COMPONENTS

Now consider the components that are assembled to make up a laser system. In the previous sections, the physical constraints that limit components have been presented. These included small-signal gain, stored energy, isolation, damage, etc. In this section component issues pertinent to fusion lasers are presented. The components functions included here are pulse generation (oscillation), amplification, spatial filters and relays, and isolators.

OSCILLATORS

The generation of the desired laser pulse shape for injection into a power amplifier chain is the subject of oscillator design. As intense a pulse as possible is desired, consistent with damage limits. It must possess the desired pulse shape in time, the desired bandwidth, and the desired spatial shape. In particular, a time-bandwidth-limited, Gaussian-in-time, single-transverse spatial-mode pulse is usually desired for subsequent spatial and temporal pulse shaping and amplification (Fig. 46).

FIG. 46. Gaussian spatial and temporal pulse.

The literature of oscillator design will not be reviewed here other than to present some of the basic ideas relevant to fusion lasers.

In an earlier section, an example illustrated the development of laser radiance as the initial fluorescence noise passed through a sufficiently long amplifier medium. In this way, the very low radiance associated with spontaneous emissions of $\approx 10 \text{ W/cm}^2/\text{sr}$ was amplified to the $> 10^{17} \text{ W/cm}^2/\text{sr}$ required for target irradiation. However, unless the frequency and spatial development of the electromagnetic wave is constrained, several spatial and temporal modes of radiation will be amplified (in a random, uncontrolled manner) at the same time. They will coherently interfere (beat) to produce large fluctuations. Consider a volume of laser material that has a gain vs frequency profile as shown in Fig. 47.¹⁰³

The number of possible free-space modes available with a typical laser material are $\nu = 3 \times 10^{14} \text{ Hz}$ ($\lambda = 1 \mu$) and $\Delta\nu = 3 \times 10^{10} \text{ Hz}$ ($\Delta\nu = 1 \text{ cm}^{-1}$). Then $N = 2.5 \times 10^9 \text{ modes/cm}^3$, and in a 1-cm-diam by 10-cm-long crystal, $N \approx 2.5 \times 10^{10}$ modes. The purpose of an oscillator is to allow only a selected number of these modes to be amplified and to propagate.

If mirrors are added around the radiating gain medium to form a resonator "cavity,"¹⁰⁴⁻¹⁰⁷ two things occur:

- 1) The spatial directions over which oscillation can occur are limited.
- 2) The frequencies that can build up in amplitude are fixed by the boundary conditions on the standing wave in the cavity.

The bandwidth is reduced because the photon time in the cavity is increased from ℓ/c to $\ell/c(1 - R)$. In addition, the mirrors force a periodic boundary condition, which forces stable electric field modes to occur only at frequency intervals of $\Delta\nu = n(c/2\ell)$, where $n = 1, 2, \dots$ [see Figs. 48 and 50(a)].

The oscillation condition is best satisfied for the mode closest to the peak of the laser gain vs frequency curve for the medium. Note that for short cavities the spacing between modes $c/2\ell$ is large, and if $\Delta\nu$ is small, the cavity mode can actually miss the laser gain line; thus oscillation will not occur. This can happen in long-wavelength gas lasers.

Number of definable E M modes in laser medium above:

$$N = 2 \cdot \frac{4\pi\nu^2}{c^2} \cdot \frac{\Delta\nu}{c} \cdot V$$

Polarizations
Diffraction-limited propagation directions per cm^2
Distinguishable frequencies per unit length of material

FIG. 47. Modes in a block of laser material.

FIG. 48. Gain vs frequency profile $G(\nu)$ in a cavity is determined by the product of laser transition line-width function $l(\nu)$ and the cavity reflectivity (or mode structure) $R(\nu)$.

The use of a simple 2-mirror cavity does not sufficiently limit the mode structure of an oscillator. When a circular aperture is added to limit the spatial mode to the lowest transverse mode, this mode is called TEM_{00} (Transverse Electric Magnetic field), and it is Gaussian in spatial profile [see Fig. 50(b)].

To further control the mode structure, frequency-control elements such as transmission Fabry-Perot etalons are added [Figs. 49 and 50(c)]. This technique is used to further discriminate between natural cavity modes and to ensure that the product of pulsewidth $\times$ bandwidth product is near unity for the desired final

FIG. 49. Use of a Fabry-Perot etalon in a laser cavity where the etalon thickness L is much shorter than the cavity length ℓ provides additional gain vs frequency modulation.

FIG. 50. Summary of oscillator-mode selection techniques used in bandwidth-limited, mode-locked, and Q-switched oscillators.

FIG. 51. The top series of pictures shows a temporally smooth oscillogram on the left and a smooth streak-camera trace in the middle.¹⁰⁸ The Fabry-Perot spectrum on the right shows only one mode oscillating. The lower series of pictures shows a slightly skewed oscillogram, extensive modulation on the streak trace, and two competing modes in the Fabry-Perot spectrum.

output pulse. That is, if a 1-ns FWHM Gaussian output pulse is desired, a bandwidth of $\sim 1 \cdot 10^{-9}$ or 10^9 Hz is arranged. The restriction of the bandwidth guarantees that no accidental secondary mode develops from noise (Fig. 51).

In some laser media, the laser gain line is too narrow to provide enough bandwidth to amplify short pulses. The line width must then be modified, usually with pressure, to provide an acceptable gain bandwidth for oscillation and amplification.

Finally, in order to produce a stationary mode in an oscillator cavity, the fields must build up slowly enough so that all nonstationary (transient) modes decay. For these reasons a time-variable loss element is added to the cavity, as shown in Fig. 50(d). In addition, by modulating the loss element at a rate equal to the round-trip cavity time $2\ell/c$, bandwidth-limited pulse build-up is forced to cycle through the oscillator at the round-trip cavity time $2\ell/c$. This technique is called "mode-locking,"¹⁰⁹⁻¹¹¹ because several resonator modes are forced, or locked together, to provide enough bandwidth to sustain amplification of a pulse whose bandwidth is wider than the width of the individual resonator modes.

The techniques described above are used extensively in all laser oscillators. In particular, these have been applied to the problem of producing stable pulses from Nd:YAG oscillators for injection into our Nd:glass laser amplifiers at Livermore.¹¹² Examples are shown in Fig. 52.

FIG. 52. Top oscillogram shows a train of mode-locked pulses from a mode-locked amplifier. The time between them is the round-trip cavity time $2\ell/c$. The middle trace shows a missing pulse that was switched out of the oscillator pulse train and into the amplifier chain. The bottom trace shows the single switched-out pulse ready for pulse amplification.

FIG. 53. A phase- and amplitude-stable Gaussian oscillator pulse can be coherently added to itself in an interferometer to obtain time-shaped laser pulses for target experiments.

Summary

The optical field in the oscillator cavity is allowed to build up gradually, developing a Gaussian time-bandwidth-limited temporal pulse, a Gaussian spatial profile determined by the lowest-order diffraction-limited mode, and a radiance determined by stored energy, materials damage limits, and the diffraction limit of the beam diameter. In addition, no secondary pulse trains (prepulses) should be present because the time-dependent loss modulation at $2f/c$ prevents their growth, and no temporal substructure should be present because of the limited available bandwidth. Such an oscillator pulse is very well behaved and can be coherently amplified, so that its radiance and total energy are increased to levels of interest for plasma experimentation. In addition, since the pulse is phase-stable in time and space, it can be conveniently manipulated for special experiments

For example, it can be spatially truncated to cause its Gaussian transverse shape to fill the initial limiting amplifier apertures.⁹⁶⁻⁹⁸ In addition, specific temporal pulse shapes can be "carved out" for special experiments, and pulses can be coherently added together (Fig. 53) if needed.^{113,114}

Finally, both the start time and build-up rate in a secondary oscillator can be accurately controlled by using a primary or master oscillator to inject "seed" pulses into the secondary oscillator.¹¹⁵ This pulse can then be used for diagnostic or pulse-shaping purposes (Fig. 54).

FIG. 54. Regenerative pulse shortening is a technique used to obtain a diagnostic pulse, synchronizable to ± 5 ps with respect to the master pulse. Coherent pulse stretching provides time-lengthened pulses. AMQ Osc means acoustic mode-locked and Q-switched oscillator.

AMPLIFIERS

Once the desired optical pulse shape has been generated by the oscillator, it must be amplified to the desired intensity, increasing the beam radiance from that developed in the oscillator to the level required for target experimentation. This process requires the selection and building of amplifiers that increase the beam radiance level, not reduce it; the amplifiers must also be cost optimized (see Fig. 55).

In the introduction to this report, the types of laser-amplifier gain media available to the laser designer were discussed. The tradeoffs between large and small amplifiers, limits to beam propagation, and stored energy and extractable energy were introduced. In this section the amplifiers themselves and the parameters available to the system designer to modify the amplifying medium are described. Since a great deal of the cost of a large laser system is in the amplifier, an understanding of the cost vs variable parameters is important.

Virtually all high-power laser amplifiers operate on the principle that the laser-gain medium is a temporary energy store, which integrates "low-grade" electrical energy and stores it in atomic or molecular transitions, until laser-pulse extraction occurs. The exception is the chemical laser, which converts chemical potential energy into an excited intermediate species ready for extraction by the laser beam. However, chemical lasers for pulsed-amplifier applications require excitation of the interaction region via a trigger signal to set off the reaction. The KrF laser amplifier does not store energy at a very high density, but it does the storage with a high efficiency. Thus techniques using multiple short pulses to extract energy efficiently from the long-pulse KrF system have been devised.

FIG. 55. Laser amplifier uses low-grade electrical energy to prepare atomic or molecular species for coherent light amplification. Typical efficiencies of electrical to photon energy are 0.5–10%. Figures of merit for amplifiers are added energy/\$ or added power/\$ for fixed-aberration contribution.

At present, two sources of excitation energy are of interest to the laser designer—photons and electrons. They are relatively easy to generate and control and most importantly have interaction lengths (energy deposition lengths) compatible with useful transverse laser dimensions as well as mechanical and electrical engineering constraints. Since these sources are used incoherently, they are constrained to excite the medium transversely. (Concepts exist to use coherent sources, such as other lasers or high-brightness electron beams that permit longitudinal interactions; however, these will not be discussed here as they are not yet prevalent.) With transverse interaction, a choice of radial illumination or simple two-sided illumination is available.

The radial-pumping geometry in Fig. 56 shows a configuration used most frequently with low-repetition-rate, photon-pump systems (Nd:glass, I_2). Its main advantage is that a maximum solid angle is available for energy input into the medium. Another advantage is that the radial convergence of pump photon fluence tends to overcome the energy depletion of the pump light as it propagates toward the center, yielding a more-uniform gain profile. The right drawing in Fig. 56 shows the geometry used for rapid-flowing gas systems, and for systems transversely excited by high-voltage electrons or by drift electrons accelerated in a one-dimensional field. Examples are CO_2 laser systems and KrF laser systems.

In all cases the object of the amplifier design is to:

- Store as much energy per unit volume consistent with the excitation source brightness and medium de-excitation due to excited-excited collisions, amplified fluorescence depumping, and parasitic thresholds. The objective of a high-stored-energy density arises because amplifier costs are proportional to the volume of the machine.

FIG. 56. Transverse pumping geometries.

- Provide an efficiency of excitation consistent with system strategy—that is, minimum total initial cost or minimum operating costs. At present, the predominant economic motivation for all experimental systems is to reduce the initial capital cost, whereas the motivation for reactor-compatible lasers is to maximize efficiency to reduce both operating and capital costs.

- Produce the gain medium with a satisfactory optical quality such that the beam radiance is enhanced. Phase uniformity and gain uniformity are emphasized.

The introduction of an amplifier medium into a propagating laser beam always deteriorates the phase quality of the beam. Modern optical-fabrication techniques permit less than 0.5λ aberration across the aperture of solid-state amplifiers, and careful attention to gas dynamics permits local density gradients $\Delta\rho/\rho < 10^{-4}$, which leads to comparable or lower optical aberrations in a gas-laser amplifier. As a result, both total beam energy and the beam radiance increase with the addition of an amplifier, because the added amplifier medium increases the beam radiance with the amplifier gain at a greater rate than the radiance decreases because of aberrations. Hence, the radiance increases to a level of interest for target experimentation. In any experimental situation, the focal quality is a function of target design and one can trade off the expense associated with better quality optics against realistic requirements associated with the laser-target experiments.

Several gain media are being used in fusion lasers. The Nd:glass laser and the CO_2 laser are given as examples to show the influence of the parameters of the medium on amplifier design.

Nd:GLASS MEDIUM

The Nd:glass laser is based on the lasing properties of the rare earth neodymium in an amorphous glass host.¹⁸⁻²⁰ The concentration of the Nd ion in the glass host is $\sim 2 \times 10^{20} \text{ cm}^{-3}$. Its decay rate is 300–600 μs , dominated by ion–ion de-excitation. Because the host is amorphous glass, each neodymium ion finds itself in a slightly different site. Thus the line width is an inhomogeneous collection of individual lines, each with $\Delta\lambda \approx 20 \text{ cm}^{-1}$, leading to a total line width of 100–200 cm^{-1} .^{21,116} This line width is very attractive because it sustains ultrashort pulse propagation. Figure 57 shows the line shape of a fluorophosphate laser glass.

FIG. 57. Fluorescence line shape of fluorophosphate laser glass.

FIG. 58. Nd:glass laser disk amplifier, for 34 cm diam laser beam. The small-signal gain (e^{L_1}) is ~ 1.5 , with 150 kJ input to the xenon flashlamps. The "planar" pumping geometry yields $\sim 2\%$ pump efficiency. The laser disks are 3-cm-thick Nd-doped fluorophosphate laser glass.

This system is photon excited, using broadband xenon flashlamp illumination (see Fig. 58). The typical absorption length ($1/e$) for the broadband pump photons in laser glass is about 3 cm for a Nd doping of $2 \times 10^{20} \text{ cm}^{-3}$. Absorption length can be varied by increasing or decreasing the Nd concentration. For beam diameters larger than the typical 3-cm photon path in $2 \times 10^{20} \text{ cm}^{-3}$ -doped (2%) laser glass, either the doping in a rod must be reduced to increase the photon path or the thin Brewster disk geometry must be

FIG. 59. With transverse optical pumping of glass laser media, the photon mean path λ_p determines the size of the amplifier. Disk geometry permits very large diameters, subject to internal parasitic constraints, not uniformity of pumping.

used.^{48,117,118} Figure 59 shows the geometry of disks and rods. In a disk, the thickness and Nd doping level are optimized to store energy efficiently and satisfy propagation constraints.

The glass laser typically stores about 300–500 J/liter in the disk ($0.3\text{--}0.5\text{ J/cm}^3$). It is interesting to note that this storage density reduces to 30–50 J/liter of amplifier space, similar to gas-laser systems, because the disk volume is about 1/10 the amplifier volume. The specific gain for a silicate material (Owens-Illinois ED-2 or Hoya LSG-91H) is $0.149\text{ cm}^2/\text{J}$. Since $0.3\text{--}0.5\text{ J/cm}^3$ is deposited in the inversion, this leads to a gain coefficient of $0.05\text{--}0.08\text{ cm}^{-1}$. The saturation fluence is typically 5 J/cm^2 (at 1 ns). This saturation fluence is attractive for pulsed lasers ($>1\text{ ns}$) because it permits reasonable energy extraction at fluence levels below surface-damage thresholds.

Small, high-gain amplifiers (preamplifiers) are almost always needed to boost the oscillator output to the level of $\sim 1\text{ J/cm}^2$ over an approximate 2-cm transverse dimension. This beam size and energy level are convenient for measurement, the intensity is within conservative propagation limits, and the size is ready for injection into a power-amplifier chain. This can be done by transversely pumping a glass rod.¹¹⁹ The photon absorption length is comparable to the rod diameter; thus, uniform high gains (~ 100) are available. The rod gain is chosen to keep the gain within bounds imposed by stability constraints.

An attractive feature of Nd in glass is that the Nd-ion-gain storage time is long ($\sim 300\text{ }\mu\text{s}$), permitting the use of low-cost, straightforward electrical-pulse discharge technology. Since electrical-energy storage is a large fraction of system costs, this is a positive factor in reducing initial capital in building a research laser.

The dynamics of glass pumping are as follows.¹²⁰ The pumping occurs from the periphery, and the total Nd population that can be excited is constrained by the radiance of the xenon flashlamps. The lamps radiate 50 J/cm^2 of broadband light. This is divided by the packing fraction of lamps, which is about 2. Thus the cylinder around the glass gain media emits $\sim 25\text{ J/cm}^2$ with the 80% efficiency of a xenon lamp. Typical transfer efficiencies from lamp-to-stored-inversion in a disk laser glass are 1.5%; the 25 J/cm^2 radiated leads to $\sim 0.4\text{ J/cm}^3$ stored in 3-cm-thick disks. This results in a small-signal gain coefficient of $\alpha = 0.06\text{ cm}^{-1}$. For a gain of $\exp(\alpha\ell) = 10$ per amplifier stage, 38 cm of gain path is needed. This requires 32 cm of plate thickness. Since the beam propagates in a skew direction through the plates, the total path is 1.2 times the disk thickness. This path can be composed of eight 4-cm-thick disks. With a gain coefficient $\alpha = 0.06\text{ cm}^{-1}$, the largest transverse dimension ℓ (which is $\sim 2\times$ beam diam in the disk) is defined by the disk parasitic constraint of $\alpha\ell \gtrsim 3\text{--}4$.^{45,47} Thus $\ell \leq 67\text{ cm}$ and the beam diameter would be 33 cm. This disk amplifier would be divided into four amplifiers of two disks each, as shown in Fig. 58.

As a result of the favorable stimulated-emission cross section, the reasonable energy-storage efficiency and cost, the high optical quality, and the short-pulse amplification capability, this laser system has found wide acceptance as an experimental tool. For a fusion-reactor laser, however, it suffers from low efficiency and a low thermal recovery rate.

CO₂ GAS MEDIUM

The molecular gas CO₂ has relevant laser levels that are low-lying vibrational excitations at $\sim 0.1\text{--}0.2\text{ eV}$ (200 cm^{-1}) above the ground level.^{22,23} The CO₂ is mixed with N₂ and He gas to enhance its efficiency. The CO₂ laser levels are easily populated by de-excitation from high-lying vibrational transitions in N₂ or CO₂. Both the CO₂ and the N₂ are directly excited by electrons moving through the partially ionized laser medium.^{121,122} Because e⁻ or UV photon ionization can be used to generate free electrons, the transverse configuration is especially useful for applying a sustainer electric field of 3–5 kV/cm to accelerate the electrons to excite the N₂ and CO₂ vibrational excitations.^{123–126} A sketch of the geometry is shown in Fig. 60.

The advantage of CO₂ excitation by electrons is that the medium can be scaled to very large transverse dimensions, because the range of pre-ionizing electron can be very long. The transverse diameter is limited only by parasitic modes associated with very large transverse gain lengths. The range of electrons in CO₂:He:N₂ gas mixtures is $\sim 1\text{ m}$ at 1 MeV. The actual laser excitation is provided by the "sustainer" field.¹²⁶ The energy deposition rate from the sustainer field is $V \cdot I \cdot \Delta t$ ($4\text{ kV/cm atm} \cdot 10\text{ A/cm}^2 \cdot 3 \times 10^{-6}\text{ s}$) or 120 J/liter. Because of the partition of energy in the rotational levels, $\sim 15\text{ J/liter}$ can be extracted with a single

FIG. 60. Electrons (or photons) ionize the laser gas medium. A sustainer field, represented by the voltage generator V , causes a current to flow between the anode on the left and a grid on the right.

FIG. 61. Power amplifier in the Antares laser system at LASL. The electron beam is directed radially outward into the annular gas region where the sustainer field is applied.

~ 1 ns pulse. Typical gains of 0.04 cm^{-1} are achieved in 1 atm gas. The saturation fluence is $\sim 0.10 \text{ J/cm}^2$, well below material damage thresholds of $\sim 5 \text{ J/cm}^2$ at $10.6 \mu\text{m}$. The gain line width is complex, consisting of an entire series of rotational lines around the P-branch transition at $10.4 \mu\text{m}$ and around the R-branch transition at $9.6 \mu\text{m}$, at moderate pressures. At high pressure the lines merge together.

This laser system is scalable, efficient, and moderate in cost. It provides a convenient source of long-wavelength, high-quality radiation for target-irradiation experiments.

Figure 61 shows the power amplifier in the Antares laser system at the Los Alamos Scientific Laboratories. The electron gun projects ionizing electrons radially outwards into the annular laser medium. The sustainer field supplies energy to the laser gas.

SPATIAL FILTERS AND RELAYS

Imaging elements are required in a laser chain to control the divergence and diameter of a laser beam as it is intensified. The primary element is the astronomical telescope, shown in Fig. 62. It projects a real image of the input beam farther down the chain, thus overcoming the natural diffraction of the laser beam. This device performs several functions. It expands the beam, projects the beam farther down the chain, reduces ASE, and spatially filters the beam when an aperture is added at the focus between the two lenses. The spatial-filtering function and the expansion functions have been discussed.^{80,81} The purpose of relaying is to maintain a high fill factor by imaging one laser aperture to the next and to prevent diffraction rings from forming.⁹⁹ An example is shown in Fig. 63.

The optimum length for the spatial-filter relay is determined by its imaging properties and is independent of the diameter of the filtering pinhole. This imaging property is shown in Fig. 64. It shows two adjacent filters in an optical train, in which the space between the filters is assumed to be filled with laser-component hardware. Optimum use of apertures is achieved if plane Z_N (input lens of filter N) is imaged onto plane Z_{N+1} (input lens of filter $N+1$). In addition, locations along the beam path preceding location Z_N will be imaged onto a location defined in L_N . Using the simple formulas for a two-lens system, the correct length of the filter is found to be $L_f^{\text{optimum}} = L_N/M$, where L_N = length of the optical-component train between adjacent filters and M = magnification of the filter. The magnification of the filter is the ratio of the diameter of the beam exiting the filter to the diameter of the beam entering it, $M = D_2/D_1$. (Note that this ratio is determined solely by amplifier staging considerations.) Therefore, the optimum length of a spatial filter is uniquely determined by the diameter of the clear aperture of components on either side of it (i.e., its magnification) and the length of the optical train between it and the filter immediately following it.

FIG. 62. Astronomical telescopes project real images of the beam and the laser apertures from the oscillator to the target focus lens.

Near-field beam profiles without Hunt relay element

FIG. 63. Beam propagation—diffraction and self-focusing (calculations performed with ARTEMIS computer code) (a) Combination of diffraction effects and nonlinear phase distortions produce large intensity gradients. With further propagation in nonlinear medium self-focusing enhances these gradients and reduces focusable power (b) The use of relay elements reduces diffraction effects and thereby minimizes growth of intensity gradients due to nonlinear phase distortions.

A second consideration for spatial-filter length is to prevent plasma formation in the pinhole.¹²⁷ No closure occurs if the laser pulse is short compared to the pinhole closure time. For long pulses, $\tau_2 > R_{\text{pinhole}}/v_{\text{plasma}}$, the intensity of the beam focal spot at the pinhole edge must be less than the threshold for plasma formation or the pinhole must be much larger than $v_{\text{plasma}} \tau_{\text{pulse}}$.

An example of the effect of relaying and spatial filtering on beam propagation is shown in Fig. 65. Figure 66 shows a 20-cm spatial filter used on the Argus laser system.

In Fig. 65, each line shows the propagation of a laser beam, from left to right, under different conditions. All of the initial conditions are the same: a small spot (0.8 mm diam.) obscures part of the beam and causes diffraction ripples. The beam profile is shown at propagation locations of 0, 1, 2, 3, 4 and 5 m. If a modifying element is present, such as the obscuration spot, a lens, or a nonlinear element, the element was located at the location shown and the beam profile is shown immediately upon exiting that element. In line (a) the evolution of the beam and the diffraction ripples from a 0.8 mm obscuration are shown as they propagate 5 m down a laser chain.

FIG. 64. Selection of relay length. The beam and aperture at location Z_N is imaged at location Z_{N+1} .

In (b) an element with an intensity-dependent index of refraction is placed at the 1 m location. The average nonlinear phase retardation for the radial envelope of the laser beam was $\sim 1/2$ wave ($B = 3$ rad). Notice the increase in the peak intensity of the beam compared to (a) which has no nonlinear materials. In (c) the effect of a simple relay is demonstrated (no nonlinear elements). The image at 0 m is reimaged to 4 m by the 1-to-1 image relay.

In (d) a nonlinear element is added directly upstream from the relay input. The phase aberration contributed by this element causes severe distortion downstream and prevents image formation of the 0 m position onto the 4 m position. However, the image at 1 m (at the lens, immediately after the nonlinear element) is reimaged to the 5 m location because no additional nonlinear aberrations are present. In real lasers we image from the input of one relay spatial filter to the input of the next spatial filter for this reason.

In (e) a pinhole is added to remove the high-frequency ripples associated with the small obscurations and subsequent nonlinear enhancement of its high spatial frequencies. The beam exiting the relay/spatial filter is suitable for subsequent laser amplification and propagation.

ISOLATORS

Isolators act as optical diodes, permitting light to pass in one direction but not in the other. They are used to prevent back-reflected laser light from re-entering the small diameter stages. This is accomplished by either the Faraday effect (the polarization plane of the light is rotated by an amount proportional to the strength of a magnetic field applied along the direction of propagation), or by the Pockels effect (the polarization plane is rotated by an amount proportional to the material length times the electric field). The Faraday effect is particularly attractive because of its scalability to large diameters.^{128,129} With it, forward-propagating, linearly polarized light can be rotated 45° in a right-hand sense with respect to the direction of the magnetic field. Thus, the plane of polarization of any back-reflected light will be perpendicular to that of the initial beam and can be rejected by a polarizer. The Faraday effect occurs in almost all glasses, particularly in paramagnetic glasses.

The Pockels effect occurs in ferro-electric crystals such as potassium dihydrogen phosphate (KDP) and its isomorphs.^{130,131} It achieves isolation by simply rotating the beam polarization for the requisite time period (~ 10 ns) and allowing the pulse through the crossed polarizers.

FIG. 65. Propagation of a $1\ \mu$ wavelength 14-cm-diam constant-intensity laser beam with conditions of linear and nonlinear propagation, spatial filtering, and imaging relaying. (Note: the initial obscuration is not drawn to scale.)

FIG. 66. Argus laser 20-cm-diam spatial filter. The pinhole section is directly in front of the man.

TABLE 10. Faraday rotator material properties at $1.06 \mu\text{m}$.

Designation	Ion	Verdet coefficient $V(\text{min/Oe cm})$	Refractive index	n_2 ($\times 10^{-13}$ esu)	Loss (cm^{-1})
SFS6	—	0.029	~1.8	>2.0	0.007
FR4	Ce	0.031	1.551	1.95	0.005
EY-1	Tb	0.037	1.610	1.77	0.005
FR5	Tb	0.069	1.678	2.03	0.005

The degree of isolation required in a laser chain can be calculated for a given gain per stage G . If the reflected light returns along the same path as the original forward beam, and the intensity (W/cm^2) or fluence (J/cm^2) nowhere exceeds that in the outgoing beam, then it can be shown that the extinction ratio required for polarizers is G^{-1} per stage and the uniformity of rotation required for the rotators is G^{-2} . Thus, a system consisting of successive amplifier stages with gains of 3.2 requires a polarization extinction of 100:1 (~ 20 dB) for each stage. In Faraday rotators, the magnetic-field uniformity must be such that, after one pass, less than 1% of the light is of the "wrong" polarization at any (transverse) position of the beam. This translates into a magnetic-field uniformity of about 10%. The system requirements are thus ~ 20 dB extinction ratio per stage for polarizers and ~ 10 dB uniformity for rotators.

Glass for Faraday rotators must have short optical path length to minimize nonlinear effects, absorption, and the effects of residual and thermal birefringence. Hence, a high Verdet constant V is desirable. This has led to the development of paramagnetic terbium glasses.^{57,132} Material properties for pertinent glasses are shown in Table 10.

The essential features of a Faraday rotator are shown schematically in Fig. 67.

SUMMARY

Some of the properties of the important components required for laser-chain construction were summarized in this section. The engineering of the components into a laser system is essential for successful target irradiation. A complete discussion of the engineering requirements of these systems can be found in the reports of the laboratories engaged in laser-fusion research and in reports of contractual research sponsored by the U.S. Department of Defense, which are available from NTIC.

FIG. 67. Unpolarized light reflected back from a target on the left is partially rejected by polarizer 1 and completely rejected by polarizer 2. Laser light propagating from a laser stage at the right passes through polarizer 2 and is rotated to pass through polarizer 1, then goes to the target.

LASER DIAGNOSTICS

In the laser-plasma interaction problem, a natural separation occurs at the interface between the incoming laser beam and the plasma. While this interaction regime is not strictly defined, a common experimental approach is to specify the initial-beam focal conditions at the target-vacuum interface. A model is then attempted, in a self-consistent fashion, of the time evolution of the interaction, knowing the time evolution of the laser pulse and the physics of the light-plasma interactions.¹³³ The complete description of this interaction is the subject of a great deal of research. Present practice is to provide as complete a description of the laser input as possible, in order to set the initial conditions between laser and target. Then, subsequent comparison between target performance and target simulations can be used to distinguish between competing models.

It is difficult to completely diagnose the laser performance because it is time consuming, expensive, and probably unnecessary. The instruments for measuring the laser interaction are, in many cases, as close to the state-of-the-art of development as are the laser and targets. The best diagnostic would be a motion picture of the beam-target interaction with picosecond framing over focal intensities from $\sim 10^{13}$ W/cm² (at plasma initiation) to peak intensities of $\sim 10^{15}$ W/cm², and down the trailing edge of the pulse. The spatial resolution should be on the order of the diffraction spot. Such complete dynamic range and information content is not presently possible. With a minimal set of diagnostics it is possible to be sure that the laser focal spot is reasonably well behaved and that all subsequent target behavior is due to the "mysteries" of plasma response, not laser performance. A typical laser-target diagnostics set is shown in Fig. 68. The techniques shown in these notes are those used at Lawrence Livermore Laboratory for the 1.06- μ m laser systems. Other laboratories use similar techniques but with important variations because of special problems caused by the availability of special optics and diagnostics at other wavelengths.

VITAL MEASUREMENTS

Proper laser operation is ascertained by monitoring at the points described in Fig. 68. Accurate measurements of the beam energy along the laser chain from oscillator to focal lens, when correlated with beam images and focusable energy measurements, give the operator confidence that the laser chain is operating correctly. A correlation between easily obtained laser-diagnostic indicators and measured laser

FIG. 68. Diagnostics are: (1) Oscillator performance and chain input beam quality. The oscillator pulse duration, spatial shape at the input to the chain, and the input energy. (Prepulses are usually too small to measure here.) (2) Beam quality at an intermediate chain location. The energy level is used to determine amplifier chain performance, time-integrated beam photographs to determine the quality of image. Damage spots, self-focusing, apodization, etc., are observed. (3) Incident-beam diagnostic station. The beam quality at the exit of the laser chain is measured here. These measurements include energy, the pulse shape in time, a time-integrated near-field beam image to determine propagation quality, a far-field diagnostic location, and a diagnostic location to image chain points back toward the oscillator for pinhole alignment. (4,5) Return-beam diagnostic location. This location is used to image both the target and the opposite beam's focal quality. The reflected beam energy, spectra, and time-evolution diagnostics are located here. Also located here are automatic laser-target pointing sensors.

focal performance is one of the most important activities in laser-system maintenance, because the resources or time to constantly verify laser focal quality generally are not available.

The most important diagnostics for the laser-target irradiation are the "far-field" diagnostics¹³⁴ shown in Fig. 69. They are usually accomplished by using secondary optical systems to measure the focal spot on the target (1), and to stimulate the focal spot with a secondary far-field focal system (2).

FIG. 69. Schematic of incident-beam diagnostic package (2), and two target viewing packages (1) and (3).

Each of these systems works by using an objective lens to image or to re-image an object onto an imaging device such as a vidicon for real-time observation, or onto sensitive film for pulse recording. System (1) (Fig. 69) re-images plane T, usually the front target surface, onto a vidicon. Using this device the laser focal size is set, and if the target is transparent, the target is positioned with respect to the beam and the beam size is adjusted (see Fig. 70). A low-level cw laser, coincident with the pulsed oscillator beam, is used for most of this work, because it has been found¹³⁵ that the cw-beam focal properties simulate the aberration and focal properties of the fully pulsed laser chain satisfactorily.

For diagnostic system (1) in Fig. 69, the primary objective lens is usually the focusing lens on the opposite incoming laser beam. For the lens to serve as an imaging objective for the target plane T, it must be used at its designed focus and within its somewhat narrow field of view. The secondary lens system is chosen to obtain the desired magnification.

System (2) (Fig. 69) is similar, except that it is designed to diagnose the incident laser beam (IBD diagnostic) by directly imaging a fraction of the incoming laser beam. The beam passes through a turning mirror and is focused onto an imaging device or through a pinhole and into a calorimeter. This diagnostic then measures "far-field" or focal-plane energy distribution and, when directed onto a streak-camera slit, far-field time duration at this location can also be measured. At this location prepulse diagnosis is also performed. For this diagnostic to accurately record full-power laser performance, its effective image position must be the same as that of the laser focal spot on the target. Figure 71 shows the Argus incident-beam system.

Finally, a third system (3) (Fig. 69) has also been used¹³⁶ to record the image of a focused beam on a target by imaging the scattered light from the focal spot onto an imaging sensor. This technique is sometimes useful for examining the focal distribution on an opaque target, but it is difficult to implement on transparent targets.

The accuracy with which systems (1), (2), or (3) replicate the actual radiation distribution at the target depends on the quality of the optical components in each diagnostic optical train. A great deal of care must be taken to be certain that the images obtained with each of these systems correspond to the actual distribution.

In a typical setup at L.L.L. on a well-instrumented laser system such as Argus, the following measurements are made:

- Oscillator
 - Oscillator pulse-train shape and intensity.
 - Oscillator switch-out pulse energy.
 - Streak camera image of input pulse to chain.

FIG. 70. Target ball (100 μm diam) showing position of incoming laser beam.

FIG. 71. Argus incident-beam diagnostic system.

FIG. 72. Near-field camera—laser-energy distribution.

- Laser chain
 - Energy at 4-cm rod, prepulse energy.
 - Energy and beam profile (see Fig. 72) at exit from 10-cm disk amplifier.
- Incident-beam diagnostic
 - Laser-output energy.
 - Laser-output pulse shape (100:1 dynamic range).
 - Laser far-field energy, through pinhole.
 - Laser focal pattern at various locations in front of, at, and behind target plane.
 - Prepulse diagnostic—70 dB ahead of pulse peak.
- Return-beam diagnostic package
 - Reflected energy.
 - Reflected target image.
 - Reflected pulse shape.

LASER SYSTEMS

The assemblage of laser components and diagnostics for target experimentation is a laser-target system.¹³⁷⁻¹⁴¹ The effectiveness of this system as measured by single-shot performance (TW or kJ)/\$, by the number of successful shots per day, by the cost of operation, or by overall electrical efficiency, is influenced greatly by the manner in which the system is assembled.

Present research laser-target systems are designed to maximize performance and to minimize capital cost. The number of experiments per day and the cost of operations, while necessary considerations, have been of lesser importance than initial cost. Electrical efficiency is not important for research lasers, except to reduce the capital cost of the laser electrical power system. As fusion lasers make the transition from very low-duty-cycle systems to reactor drivers, emphasis is shifting to overall efficiency and low maintenance costs, with capital cost being a lesser consideration.

Primary system considerations are:

- Laser architecture.
- Fluence and aberration limits.
- Component efficiency.
- Quality of engineering and physics design

Laser architecture influences the overall size (length and diameter) of the system, thus fixing the cost-per-beam aperture and strongly influencing related costs such as building space, maintenance equipment, etc. Fluence-limits fix the aperture size required to meet a given power level and the amount of amplification required to bring a beam from the oscillator output to a fluence-limited output area. Aberration limits constrain the length and optical quality of the laser medium. Component cost, especially amplification, is generally proportional to diameter squared and to electrical efficiency. In many components, such as the amplifiers and Faraday rotators, the electrical-system cost is two thirds of the total component cost; thus efficiency influences the component cost. Finally, good engineering design layout, conservative operational levels, and proper execution of this system consistent with laser-physics constraints are essential in meeting objectives and having a system that can be reliably operated.

GENERIC SYSTEMS

Figure 73 shows three generic forms of system architecture. The master-oscillator power amplifier (MOPA) system is the most common fusion-laser system and is used exclusively at LLL. A low-level bandwidth-limited pulse is injected into pulse amplifiers, which increase the pulse energy to levels consistent with propagation constraints. By selection of the rate of beam expansion and amplifier medium, reasonable extraction of stored amplifier energy occurs within the constraints of fluence limitations. The disadvantage of

this system type is that a large number of amplifier sizes and optics are required and many amplifiers are not operated at full-beam fluence: thus their stored energy is not efficiently extracted. The positive attributes are that this system design is relatively straightforward, the propagation issues are clear, the beam travel distance is minimal, and the linear aberrations of the beams are averaged as the beam traverses the many laser components. Finally, it is the only system (until recently) that has been physically realizable with the present understanding of laser design and components. As a result, most operating fusion-laser systems are of this design. Examples are the Livermore Argus and Shiva lasers.

The second and third types of laser systems, shown in Fig. 73, are variations of the multipass geometry.^{142,143} The primary object of these geometries is to extract as much of the stored energy as possible from a single amplifier system, thus avoiding the need for a multiplicity of components and inefficiently used amplifiers. The regenerative laser system in Fig. 73 is, with some variation, the usual oscillator geometry used for generating low-level pulses. The problems associated with the off-axis multipass system are the long propagation paths required to reduce beam vignetting at the amplifier aperture and the need to use large-diameter components to make proper use of economics of scale. The major problem with the switched regenerative system is the attainment of a large-diameter optical switch that has a rapid switching time (consistent with cavity length), low leakage to prevent prepulse, and low-loss optical components. In both multipass geometries, the repetitive cycling of the optical beam through the same components leads to cumulative aberration buildup. The second and third systems are especially sensitive to intracavity losses, because unless the round-trip loss is low, the amplifier energy that is transferred to the laser optical field is in turn deposited in the cavity losses and not stored in the optical field for eventual deposition on the target. The switch in the regenerative system is quite prone to excess loss.

FIG. 73. Storage laser media—system architecture.

FIG. 74. Two-pass amplifier design used in Nd:glass laser systems.

While the examples in Fig. 73 were chosen to illustrate three basic ideas in laser-system architecture, many innovative hybrid variations have been used. For example, in Fig. 74 it is common to use a Faraday rotator to pass a beam through a glass-laser disk amplifier.¹⁴⁴ This technique is useful primarily for low-level beams because of the damage level associated with the polarizer and rotator at the output section.

Similarly, one can multipass a final-amplifier stage as in Fig. 75 to raise a low-level beam to a fluence level sufficient for an ultimate extraction pass as on the Helios CO₂ laser at Los Alamos.^{140,145}

Other variations have been proposed and tested. Difficulties have arisen with schemes similar to those above because of fluence limitations, nonlinear aberrations, and parasitic oscillation limitations. To be effective, these multiple-use schemes must satisfy the same constraints as any other system.

SYSTEM DESIGN

A common thread in all laser-system designs is the idea of transferring energy from stored atomic-inversion energy to electromagnetic beam energy in a performance-optimum fashion.¹⁴⁶ This transfer of energy occurs efficiently when the beam fluence exceeds the saturation fluence of the laser medium. For example, saturated fluences are 4–5 J/cm² in a 1-ns pulse in Nd:glass laser or 0.1 J/cm² at 1 ns in a 1-atm CO₂ amplifier. In addition, the laser beam should propagate at a fluence near a propagation limit usually defined by

FIG. 75. Three-pass amplifier design used in the Helios CO₂ laser system.

FIG. 76. Examples of system design, showing how amplifier size and beam expansion influence system costs.

dielectric breakdown ($3\text{--}15 \text{ J/cm}^2$), or by nonlinear effects such as self-focusing or two-photon absorption. Unless the system is operated at or above a saturation fluence, energy stored in the amplifier medium is left unused and, unless operation occurs near a breakdown fluence, optical area is purchased that is not required. In addition to these laser fluence considerations, cumulative linear and nonlinear propagation effects will also constrain system performance. In summary, the following considerations determine system operating levels.

- Damage limits.
- Accumulation of nonlinear phase distortion.
- Accumulation of linear phase distortion.
- Amplifier energy storage (gain) vs system loss.

As examples of these considerations in system designs, consider the systems in Fig. 76. The purpose of each system is to amplify the oscillator pulse from the $\sim 1\text{-mJ}$ oscillator output to a fluence limit imposed by the exit aperture area and the length of propagation. However, system (a) in Fig. 76 is too expensive. Amplifier 1 is not used efficiently; the laser intensity is well below the saturation fluence and propagation limits; thus little of the (expensive) stored energy is extracted. In addition the gain of a larger-diameter amplifier is usually lower than the gain in smaller-diameter amplifiers like those used in the early stages of (b) and (c). Thus additional amplifiers are required, imposing larger propagation distances through gain media and accumulating additional beam aberrations. Concept (a) however, could be used in multipass systems (e.g., the multipass system in Fig. 73, where amplifier 1 replaces amplifier 2 to n , and the low extraction efficiency per pass is overcome by reusing the amplifier many times. When propagation constraints are satisfied, this technique is thought to be efficient.

System (b) in Fig. 76 is a conceptually simple approach to matching the rate of increase in laser-beam intensity to the increase in amplifier diameter. The rate of divergence of system (b) is set by the amplifier gain and the accumulation of aberrations. A rapid divergence is associated with high-gain amplifiers (non-saturated) and short path length to limit nonlinear aberration accumulations; a longer, more gentle taper is

associated with saturated gain and more gradual accumulation of nonlinear aberrations. The system, as it is portrayed in Fig. 76 (b) with a continuously expanding beam, does not provide for image relaying.

System (c) in Fig. 76 is the arrangement for present Nd:glass laser systems. The growth of the beam diameter is optimized to extract energy from the amplifier as efficiently as possible and to stay within damage limits and nonlinear-aberration limits. The use of expanding telescopes to increase beam diameter also permits relay imaging and spatial filtering to be done conveniently. Each *stage* contains the necessary components for isolation, amplification, and imaging and meets nonlinear and linear propagation constraints.

SUMMARY OF SOME RULES FOR LASER-STAGE DESIGN

- The gain length within a given amplifier stage must be such that there is no internal stage oscillation.
- Linear and nonlinear aberration constraints are satisfied and damage limits are not exceeded.
- The amplifier diameter is selected to amplify the low-level oscillator signal as cheaply as possible to an output level determined by the propagation limitations associated with both the output aperture and the cumulative aberration limits.

STAGING

Laser chains are conveniently divided into stages. The system in Fig. 76 (c) is examined in more detail as it is a common design and the ideas are easily applied to similar chain configurations. Figure 77 shows a stage of this chain. This stage consists of an input element, in this case a lens with a coating (1); an amplifier stage with gain; a loss element, which includes losses and aberrations on windows, disks, Faraday rotators, lenses, etc.; and an exit element, in this case coated or uncoated lenses (2).

Because of the variation in component performance with laser-pulse duration, the stages, and consequently the laser system, can be optimized only at one pulse duration. The performance of the system at another pulse duration, while adequate, will be less than optimum because the system is not optimized at that specified pulse duration. Three clear regimes of system design occur, limited by the above constraints. The short-pulse operation region (< 50 ps) is where nonlinear-aberration constraints are dominant, the intermediate-operation regime is where surface-damage constraints limit performance, and the long-pulse operation regime is where the laser-gain (stored energy)-stage-loss ratio determines performance. Examples of lasers in each regime are short-pulse (50 ps) Nd:glass laser systems, which are nonlinear-aberration dominated, the CO_2 laser system operating at ~ 1 ns, which is damage limited, and the KrF system at ~ 10 ns, which is stored-energy limited. Figure 78 shows the regimes of operation for Nd:glass lasers.

FIG. 77. A typical stage in a laser chain.

FIG. 78. A laser chain is constrained in its optical output by different phenomena at different pulse durations.

Laser-system designs are optimized at a single-pulse duration. For a Nd:glass system, the dominant limiting mechanisms are shown. Other systems are constrained by similar limits. The constraints are summarized below:

1. Nonlinear aberrations limit short-pulse performance:

$$B = \frac{2\pi}{\lambda} \int_{\text{input}}^{\text{output}} \gamma l \, dl < \text{constraint} \sim 4 \text{ rad of nonlinear retardation between spatial filters.}$$

In this case nonlinear aberrations accumulate rapidly and deteriorate beam focusability before damage limits are reached. With ultraclean relayed systems this constraint may be relaxed somewhat to $B \approx 4$.

2. Damage levels of the output aperture limit the total laser fluence:

$$\mathcal{E}_{\text{laser}} \leq \mathcal{E}_{\text{damage}}.$$

3. Laser-beam energy is limited by the amplifier stored energy and the stage losses.

$$\mathcal{E}_{\text{beam}} \leq \frac{\alpha}{\gamma} \mathcal{E}_{\text{sat}}.$$

To optimize stages for each performance region, the components are first optimized.¹⁴⁶ In particular, a great deal of attention is paid to amplifier performance, since it is the most costly element and it contributes a major fraction of the nonlinear and linear aberrations.

Under constraint 1) above, the amplifier is optimized so that gain per unit contribution of nonlinear aberration (B integral) is maximum. In glass-disk amplifiers this means that thin, strongly pumped laser disks are selected (see Fig. 79). Amplifier electrical efficiency is sacrificed to maximize fluence through the whole stage. At the same time, the thickness of the other optical components is reduced to minimize nonlinear phase accumulation. With amplifiers so optimized, the best situation possible for chain construction is obtained. These stages are then assembled to make a laser system.^{15,79} Nonlinear-aberration constraints of < 4 rad/stage (including the focusing stage) are usual, with overall-chain (Σ stages) cumulative nonlinear aberrations of

FIG. 79. Nd:glass amplifier optimization by varying bank energy and disk thickness. Maxima for energy occur with thicker glass disks than the maxima for power performance.

~ 10 rad. Such a system optimization emphasizes small-diameter, high-gain amplifiers, thin optical materials, and short systems. See Fig. 80, for example, which shows the Argus staging consideration. The optimization of a system using chains constructed from these stages requires the consideration of the additional costs associated with each chain. These costs include chain diagnostics, automatic pointing, control, etc. When these considerations are included, it is found that larger-diameter chains are desired to minimize the number of chains and thus, total costs.

In a system where nonlinear (and linear) phase accumulation is not an issue, the design is governed by the efficiency of energy storage in the amplifier. In this case, the efficiency of the amplifier is optimized because with the constraint of either a damage limit or stored energy limit leads to the lowest-cost stage. Figure 79 also shows an example of glass laser disks in an amplifier optimized for long-pulse operation.

The total gain in the stage is determined either by the stage losses, since there is an optimum gain-to-loss ratio, or in present cascaded systems by the ratio of the damage threshold of the entrance optic to the exit optic. With present damage thresholds, the optimum technique for long-pulse system synthesis is shown in Fig. 81.

This technique, used to optimize performance in long pulse Nd:glass laser systems, is to let the exit fluence of an amplifier approach the damage threshold of uncoated optics.¹⁴⁷ The area expansion ratio of the telescope is the ratio of damage thresholds, modified by the attenuation in the peak noise due to the spatial-filter pinhole and the loss term in the first lens. Typical ratios are $\mathcal{E}_{\text{bare}}/\mathcal{E}_{\text{coated}} \sim 2$. The amplifier in the stage is optimized for energy storage to overcome the stage losses associated with the reflections from the uncoated surfaces at O_{exit}^n and to bring the beam up to the permissible fluence on element O_{exit}^n in Fig. 81.

FIG. 80. Argus staging.

Isofluence means that each stage exit aperture is used to its utmost capability. This minimizes the costs of each stage, which are proportional to the aperture area.

In summary, the steps required to optimize a laser stage are to select the laser-pulse duration and to use amplifiers optimized for the pulse regime. If the operating regime is not clear cut, that is, short-pulse nonlinear-limited or long-pulse fluence limited, or if an extremely versatile laser system is needed, amplifier parameters halfway between short-pulse and long-pulse optimized devices are selected (Fig. 79). The next step is to use optimized amplifiers to build up chain stages, subject to constraints of stage construction. These are nonlinear phase accumulations, isolation requirements, and fluence limitations. Once an optimized stage is obtained (for each diameter), the stages can be assembled into a chain, and the chains assembled into a system. This process may have to be iterated several times.

An example of a short-pulse optimized Nd:glass-laser chain is the Argus laser chain¹⁵ shown in Figs. 80 and 82. The Argus chain is nonlinear-phase-optimized (B limited) for 100-ps laser pulses. Under these conditions the nonlinear phase retardation per stage is balanced, the system is isolated against 100% target back reflection, and the laser fluence never exceeds commercial thin film damage limits. Figure 9 shows the focal characteristics of this system. The output section of the system was recently expanded to improve the long-pulse performance. Additional 1.4 $\times$ magnification from 20 to 28 cm at the amplifier exit permitted the amplifier stage to amplify the beam to greater intensity than the focusing lens could tolerate when it was 20 cm diameter, thus improving the long-pulse energy performance. The University of Rochester's Omega laser system has been designed using similar rules.¹³⁹

Another example of a laser chain is the Nova laser system shown in Fig. 83. This particular chain is optimized to be efficient from 100 ps to 2 ns. The use of a low nonlinear-index-of-refraction fluorophosphate laser glass has permitted very efficient amplifier operation within nonlinear-aberration constraints. The system is designed to become iso-fluence at ~ 2 ns, where the fluence limits permit an intense-enough laser beam to obtain good energy extraction from the amplifier. The use of uncoated lenses at the exit of each stage permits *average* beam intensities to approach $10 \text{ J}/\text{cm}^2$ at 1 ns, much higher than the $5\text{--}7 \text{ J}/\text{cm}^2$ damage limit of antireflection coatings.

FIG. 81. Expansion technique used in damage-limited long-pulse Nd:glass laser systems.

SYSTEM COSTS

The costs of a large laser system can be divided into approximately four equal categories¹⁴⁸:

- Optics.
- Electrical equipment.
- Mechanical equipment.
- Buildings and contingency.

In this report the optical performance of a laser chain has been emphasized, since a great deal of leverage is available in this area. Any increase in the fluence-handling capacity of an aperture leads to a direct

FIG. 82. Argus laser irradiation facility.

FIG. 83. Nova chain design.

increase in system performance with little cost increase. For example, the implementations of spatial filters and relay imaging have each led to significant increases in the fluence capacity of laser operations for a negligible cost increase. Also, the isofluence concept used on Nova will permit a 2X increase in aperture fluence, with a small chain-cost increase associated with extra gain to overcome the 7% loss of the uncoated exit optic. Conversely, a mistake in the physics or engineering of the optical system can lead to an enormous reduction in laser performance. Past examples have been the lack of attention to chain-target isolation, inaccurate assessments of nonlinear aberrations limits (B limits), and overly optimistic estimations of laser-optics damage thresholds.

The designs of the electrical and mechanical subsystems strongly influence the ease with which the systems can be assembled, operated, and maintained. Performance or cost improvements in these areas do not influence the total system performance dramatically as do optical-system improvements. Nonetheless, constant improvement is being made in these areas. Figure 84 shows the improvements in Nd:glass-laser-system performance with innovation and with improved cost engineering.

Experience also shows that the capital cost of a laser chain is distributed as shown in Fig. 85. As a result, a great deal of attention is paid to engineering the amplifier section, which includes isolators and spatial filters, as well as amplifiers. Since the amplifier costs scale with area, the division of the total required beam area into smaller subsections (more chains) is permitted with small cost penalties on amplifier performance. However, the diagnostics, control, and maintenance costs are very nearly the same for each chain no matter what the chain diameter. As a consequence, the use of as small a number of chains as possible is emphasized, each with as large a beam area as possible. As an example of this at Livermore, the Janus laser used an 8.5-cm-diam beam, Argus and Shiva a 20-cm-diam beam, an early Nova design a 50-cm-diam beam, and the present Nova design has a 74-cm-diam output beam.

FIG. 84. Performance/cost breakthroughs on solid-state laser systems.

FIG. 85. Fusion laser functions and costs.

THE FUTURE

Future laser systems for fusion application will be required to deposit $\sim 1-5$ MJ of energy on target in 10-20 ns pulse durations. The target irradiation rate must occur at 1-10 Hz. Such laser systems will undoubtedly be of the multipass architecture and will possess $\sim 1-3$ m diam apertures.¹⁴⁹ Gas-laser systems are favored because of the simplicity of cooling and potential high efficiency. These systems are technically feasible, but require additional work on materials to permit the highest possible fluence through the laser apertures to maintain reasonable overall system costs. The constant increase in performance per dollar, shown in Fig. 84, should continue as laser technology evolves.

REFERENCES

1. S. Colgate, R. E. Kidder, J. H. Nuckolls, R. F. Zebawski, and E. Teller, Lawrence Livermore Laboratory, Livermore, CA, unpublished calculations (1961).
2. N. G. Basov and O. N. Krokhin, "The Conditions of Plasma Heating by the Optical Generator Radiation," in *Proc. 3rd Quantum Electronics Conference, Paris, 1963*, N. Bloembergen and P. Grivet, Eds. (Columbia University Press, NY, 1964).
3. J. H. Nuckolls, L. L. Wood, A. R. Thiessen, and G. B. Zimmerman, "Laser Compression of Matter to Super-High Densities: Thermonuclear (CTR) Applications," *Nature* **239** (5368), 139-192 (1972).
4. K. A. Brueckner and S. Jorna, "Laser Driven Fusion," *Rev. Mod. Phys.* **46**, 325 (1974).
5. J. L. Emmett, J. H. Nuckolls, and L. L. Wood, "Fusion Power by Laser Implosion," *Sci. Am.*, pp. 24-37 (June 1974).
6. G. Charatis, J. Downard, R. Goforth, B. Guscot, T. Henderson, S. Hildum, R. Johnson, K. Mencur, T. Leonard, F. Mayer, S. Segal, L. Siebert, D. Solomon, and C. Thomas, "Experimental Study of Laser Driven Compression of Spherical Glass Shells," in *Proc. of the 5th IAEA Plasma Fusion Conf. in Tokyo, Japan, 1974* (Plasma Physics and Controlled Nuclear Fusion Research 1974, 2, 317 IAEA, Vienna, 1975).
7. J. F. Holrichter, H. G. Ahlstrom, R. D. Speck, E. K. Storm, J. E. Swain, L. W. Coleman, C. D. Hendricks, H. N. Kornblum, F. Seward, V. W. Slivinsky, Y. L. Pan, G. B. Zimmerman, and J. H. Nuckolls, "Implosion Experiments with an Asymmetrically Irradiated Laser Fusion Target," *Plasma Phys.* **18**, 675-680 (1976); K. R. Manes, H. G. Ahlstrom, R. A. Haas, and J. F. Holrichter, "Light-Plasma Interaction Studies with High-Power Glass Lasers," *J. Opt. Soc. Am.* **67**, 717 (1977).
8. Laser implosion experiments are being carried out by workers at Los Alamos Scientific Laboratories, Los Alamos, NM; Rutherford Laboratories, England; Naval Research Laboratories, Washington, D.C.; University of Rochester, Rochester, NY; CEA in Limeil, France; The Lebedev Institute, Moscow, USSR; and Osaka University, Japan.
9. A. L. Schawlow and C. H. Townes, "Infrared and Optical Masers," *Phys. Rev.* **112** (6), 1940-1949 (1958).
10. D. Ross, *Lasers, Light Amplifiers, and Oscillators* (Academic Press, NY, 1968).
11. *Laser Theory*, F. Barnes, Ed. (IEEE Press, NY, 1972).
12. *Laser Interaction and Related Plasma Phenomena*, Vols. 1-4, H. J. Schwartz and H. Hora, Eds. (Plenum Press, NY, 1971-77).
13. *Laser Program Annual Reports 1973-1978*, Lawrence Livermore Laboratory, Livermore, CA, UCRL-50021-73, -74, -75, -76, -77, -78. These reports are available from the National Technical Information Service, Springfield, VA 22161.
14. W. F. Krupke, E. V. George, and R. A. Haas, "Advanced Lasers for Fusion," in *The Laser Handbook*, M. L. Stith, Ed. (North Holland Publ. Co., 1979), p. 627.
15. W. W. Simmons, D. R. Speck, and J. T. Hunt, "Argus Laser System: Performance Summary," *Appl. Opt.* **17**, 999 (1978).
16. A. E. Siegman, *An Introduction to Lasers and Masers* (McGraw-Hill Book Co., NY, 1971).
17. A. Yariv, *Quantum Electronics* (John Wiley & Sons, NY, 1967).
18. E. Snitzer, "Optical Maser Action of Nd^{3+} in a Barium Crown Glass," *Phys. Rev. Lett.* **7**, 444 (1961).
19. E. Snitzer, "Glass Lasers," *Appl. Opt.* **5**, 1487 (1966).
20. W. F. Krupke, "Induced-emission Cross Sections in Neodymium Laser Glasses," *IEEE J. Quant. Elect.* **QE-10**, 450 (1974).
21. S. E. Stokowski, R. A. Saroyan, and M. J. Weber, *Nd-Doped Laser Glass Spectroscopic and Physical Properties*, Lawrence Livermore Laboratory, Livermore, CA, Misc. Report MS-095 (1978).
22. C. K. N. Patel, "Selective Excitation Through Vibrational Energy Transfer and Optical Maser Action $\text{N}_2\text{-CO}_2$," *Phys. Rev. Lett.* **13**, 617 (1964).
23. For a complete review of the CO_2 literature up to 1974 the reader should consult: O. P. Wood, "High Pressure Pulsed Molecular Lasers," *Proc. IEEE* **62**, 355 (1974).

24. See articles in: *Principles of Laser Plasmas*, G. Bekefi, Ed. (John Wiley & Sons, NY, 1976).
25. K. Hohla and K. L. Kompa, "Photochemical Iodine Laser - A High Power Gas Laser," in *Laser Interaction and Related Plasma Phenomena*, Vol. II, H. J. Schwartz and H. Hora, Eds. (Plenum Press, NY, 1971), p. 61.
26. N. G. Basov et al., *Kvant. Elektron* **6**, 116 (1973).
27. K. Hohla and K. L. Kompa, "The Photochemical Iodine Laser," in *Handbook of Chemical Lasers*, R. W. F. Grose and J. F. Batt, Eds. (John Wiley & Sons, NY, 1976), p. 667.
28. G. Brederlow, K. J. Witte, E. Fill. K. Hohla, and R. Volk, "The Asterix III Pulsed High-Power Iodine Laser," *IEEE J. Quant. Elect.* **QE-12**, 152 (1976).
29. G. A. Fisk, M. A. Gusinow, A. K. Heys, T. D. Padrick, R. E. Palmer, J. K. Rice, M. E. Riley, and F. K. Truby, *The Atomic Iodine Laser*, Sandia Laboratories, Albuquerque, NM, Technical Report SAND 78-1071 (1978), available from National Technical Information Services, Springfield, VA, 22161.
30. J. J. Ewing and C. A. Brau, "Laser Action on the $2\Sigma_1^- \rightarrow 2\Sigma_{1/2}^-$ Bands of KrF and XeCl," *Appl. Phys. Lett.* **27**, 350 (1975).
31. J. A. Mangano and J. H. Jacob, "Electron-Beam-Controlled Discharge Pumping of the KrF Laser," *Appl. Phys. Lett.* **27**, 495 (1975).
32. For an up-to-date review on the subject of excimer lasers see *IEEE J. Quant. Elect.* **QE-15** 5 (1979).
33. L. M. Frantz and J. S. Nodvik, "Theory of Pulse Propagation in a Laser Amplifier," *J. Appl. Phys.* **14**, 2346 (1963).
34. N. G. Basov and V. S. Letokov, "Propagation of a Light Pulse in an Inversely Populated Medium," *Opt. Spektrosk.* **6**, 586 (1965).
35. J. B. Trenholme and K. R. Manes, *A Simple Approach to Laser Amplifiers*, Lawrence Livermore Laboratory, Livermore, CA, UCRL-51413 (1972). The derivation of the saturated gain equations in the lecture notes are due to J. B. Trenholme.
36. For a clear discussion of Fourier optics see: J. W. Goodman, *Introduction to Fourier Optics* (McGraw-Hill Book Co., Inc., NY, 1968).
37. For a complete discussion of diffraction, focusing, aberrations, etc., see: M. Born and E. Wolf, *Principles of Optics* (Pergamon Press, NY, 1964).
38. There is an extensive bibliography on lens design that the reader should consult. The reference given is one example of lens design for laser-fusion applications. A. Greenbaum, A. J. Glass, and J. B. Trenholme, "Lens and Mirror Design via the Principal Surface," *Appl. Opt.* **15**, 2579 (1976).
39. Figures 26 and 27 were kindly supplied by Itek Corporation, Lexington, MA.
40. P. A. Renard and J. T. Hunt, *ARTEMIS—A Diffraction Model for Laser Light Propagation*, Lawrence Livermore Laboratory, Livermore, CA, UCID-17381 (1977). A. J. Glass and W. E. Warren, *Malaprop—List Propagation in a Nonlinear Medium with Stochastic Perturbations*, Lawrence Livermore Laboratory, Livermore, CA, UCRL-80316 (1977).
41. N. H. Burnett and M. C. Richardson, "Sparkgap Optical Isolator for High Power Infrared Lasers," *Rev. Sci. Instrum.* **47**, 241 (1976).
42. R. F. Benjamin, D. B. Henderson, K. B. Mitchell, and M. A. Stroschio, "Laser-Target Retropulse Isolation Using an Aperture in Vacuum," *Appl. Phys. Lett.* **31**, 511 (1977).
43. L. P. Bradley and P. Koert, *Plasma Shutter for High Power Glass Laser*, Lawrence Livermore Laboratory, Livermore, CA, UCRL-81364 (1978).
44. M. A. Summers, B. M. Carder, J. Myall, W. W. Simmons, and D. R. Speck, *Laser-Target and Laser Isolation for Shiva*, Lawrence Livermore Laboratory, Livermore, CA, UCRL-80194 (1978).
45. J. B. Trenholme, *Fluorescence Amplification and Parasitic Oscillation Limitations in Disk Lasers*, Naval Research Laboratory Memorandum Report 2480 (July 1972).
46. A. N. Chester, "Gain Thresholds for Diffuse Parasitic Laser Modes," *Appl. Opt.* **12**, 2139 (1973).
47. J. A. Glaze, S. Guch, and J. B. Trenholme, "Parasitic Suppression in Large Aperture Nd:Glass Disk Laser Amplifiers," *Appl. Opt.* **13**, 2808 (1974).

48. J. M. McMahon, J. L. Emmett, J. F. Holzrichter, and J. B. Trenholme, "A Glass Disk-Laser Amplifier," *IEEE J. Quant. Elect.* **QE-9**, 992 (1973).
49. For a discussion of amplified spontaneous emission in Nd:glass lasers, see *Laser Program Annual Report*, Lawrence Livermore Laboratory, Livermore, CA, UCRL-50021-75 (1976), p. 249.
50. D. R. Speck, *Laser Program Annual Report*, Lawrence Livermore Laboratory, Livermore, CA, UCRL-50021-78 (1979), p. 2-15.
51. Fluorophosphate Laser Glass LG-812, Information Bulletin 7513, Schott Optical Glass, Inc., Duryea, PA (1978).
52. New Hoya Glasses for High-Power Laser Systems, Hoya Glass Company, Menlo Park, CA (1977).
53. ED-2 Silicate Laser Glass, Owens-Illinois (1979).
54. Schott Optical Glass Catalog, Schott Optical Glass, Inc., Duryea, PA.
55. Ohara Optical Glass Catalog, Bous Optical Glass, Inc.
56. Hoya Optical Glass Catalog, Hoya Glass Works, Menlo Park, CA (1975).
57. Hoya Faraday Rotator Glass, Hoya Glass Works, Menlo Park, CA (1974).
58. H. E. Bennett and J. M. Bennett, "Precision Measurements in Thin Film Optics," *Phys. Thin Film* **4**, (1967).
59. N. Brown, Lawrence Livermore Laboratory, Livermore, CA, private communication (May 1979).
60. Measured values obtained at Lawrence Livermore Laboratory, Livermore, CA, and at commercial suppliers such as Optical Coating Laboratory, Inc., Santa Rosa, CA, and Spectra Physics Inc., Mountain View, CA.
61. W. Reichelt, Los Alamos Scientific Laboratory, Los Alamos, NM, and K. Manes, Lawrence Livermore Laboratory, Livermore, CA, private communication (June 1979).
62. *Compendium on High Power Infrared Laser Window Materials*, Air Force Cambridge Research Center, Cambridge, MA, AFCRC-72-0170 (1972).
63. H. Mahr, "Two-Photon Absorption Spectroscopy," H. Rabin and C. L. Tang, Eds., *Quantum Electronics, Vol. I, Part II* (Academic Press, NY, 1975), pp. 285-361.
64. P. Liu, W. L. Smith, H. Lotem, J. H. Bechtel, N. Bloembergen, and R. S. Adhav, "Absolute Two-Photon Absorption Coefficients at 355 nm and 266 nm," *Phys. Rev. B* **17**, 4620-4632 (1978).
65. R. L. Carman, R. Y. Chiao, and P. L. Kelley, "Observation of Degenerate Stimulated Four-Photon Interaction and Four-Wave Parametric Amplification," *Phys. Rev. Lett.* **17**, 1281 (1966).
66. V. I. Bespalov and V. I. Talanov, "Filamentary Structure of Light Beams in Nonlinear Liquids," *JETP Lett.* **3**, 307 (1966).
67. A. J. Campillo, S. L. Shapiro, and B. R. Snyder, "Periodic Breakup of Optical Beams due to Self-Focusing," *Appl. Phys. Lett.* **23**, 628 (1973).
68. E. S. Bliss, D. R. Speck, J. F. Holzrichter, J. H. Erkkila, and A. J. Glass, "Propagation of a High-Intensity Laser Pulse With Small-Scale Intensity Modulation," *Appl. Phys. Lett.* **25**, 448 (1974).
69. "Small-Scale Instability Growth" and "Whole-Beam Self-Focusing," *Laser Program Annual Report*, Lawrence Livermore Laboratory, Livermore, CA, UCRL-50021-74 (1975), pp. 179-205.
70. Y. R. Shen, "Self-Focusing: Experimental," and J. H. Marburger, "Self-Focusing: Theory," in *Progress in Quantum Electronics, Vol. 4, Part I*, J. H. Sanders and S. Stenholm, Eds. (Pergamon Press, NY, 1975).
71. E. S. Bliss, D. R. Speck, and W. W. Simmons, "Direct Interferometric Measurements of the Nonlinear Refractive Index Coefficient n_2 in Laser Materials," *Appl. Phys. Lett.* **25**, 728 (1974).
72. E. S. Bliss, J. T. Hunt, P. A. Renard, G. E. Sommergren, and H. J. Weaver, "Effects of Nonlinear Propagation on Laser Focusing Properties," *IEEE J. Quant. Elect.* **QE-12**, 402 (1976).
73. M. J. Weber, D. Milam, and W. L. Smith, "Nonlinear Refractive Index of Glasses and Crystals," *Opt. Eng.* **17**, 463-469 (1978).
74. C. S. Wang, "The Stimulated Raman Process," in *Quantum Electronics, Vol. I, Part II*, H. Rabin and C. L. Tang, Eds. (Academic Press, NY, 1975), pp. 447-472.
75. C. T. Hsieh, N. B. Foltz, and C. W. Cho, "Production of Stimulated Raman Lines in H_2 Gas with a Focused Laser Beam," *J. Opt. Soc. Am.* **64**, 202 (1974); and Ref. 74.

76. S. A. Akhmanov, A. I. Kovrygin, and A. P. Sukhorukov, "Optical Harmonic Generation and Optical Frequency Multipliers," in *Quantum Electronics, Vol. 1, Part III*, H. Rabin and C. L. Tang, Eds. (Academic Press, NY, 1975), pp. 476-586.
77. J. F. Holzhrichter and D. R. Speck, "Laser Focusing Limitations from Nonlinear Beam Instabilities," *J. Appl. Phys.* **47**, 2459 (1976).
78. J. A. Glaze, "High Energy Glass Lasers," *Opt. Eng.* **15**, 136 (1976).
79. The derivation of the *far-field* growth of small-scale, self-focusing instabilities has been done by J. B. Trenholme; the only available reference is in the *Laser Program Annual Report*, Lawrence Livermore Laboratory, Livermore, CA, UCRL-50021-76 (1977), p. 2-337.
80. W. W. Simmons, S. Guch, Jr., F. Rainer, and J. E. Murray, "Terrawatt Laser Performance," *IEEE J. Quant. Elec.* **QE-11**, 31D (1975).
81. A. Bettinger, C. Charles, J. Osmalin, and J. G. Giraud, "Laser Beam Brightness Improvement with High Power Spatial Filtering," *Opt. Commun.* **18**, 176 (1976).
82. An excellent history and review on the subject of laser-materials damage problems is *Laser Induced Damage in Optical Materials*, 1978, A. J. Glass and A. H. Guenther, Eds. (NBS Special Publication 541, 1978).
83. Also see the review article by A. J. Glass and A. H. Guenther, "Material Limitations in Fusion Lasers" in *Critical Materials Problems in Energy Production* (Academic Press Inc., NY, 1976).
84. These experiments showing the onset of laser damage were performed by D. Milam, W. H. Lowdermilk, and F. Rainer. The SEM photographs of the damaged samples were kindly provided by G. Carrier of Corning Glass Works, Corning, NY. For details of the experimental techniques, see D. Milam, "Measurement and Identification of Laser-Damage Thresholds in Thin Films," *Opt. Coatings-Applications and Utilization II, Soc. Phot. Instrum. Eng.* **140**, 52 (1978).
85. N. L. Boling, G. Dube, and M. D. Crisp, "Laser Surface Damage Studies on Several Glasses," in *Laser Induced Damage in Optical Materials* (NBS Special Publication 387, 1973), p. 69; J. H. Apfel, E. A. Enemark, D. Milam, W. L. Smith, and M. J. Weber, "The Effects of Barrier Layers and Surface Smoothness on 150 ps, 1.064 μ m Laser Damage," in *Laser Induced Damage in Optical Materials* (NBS Special Publication 509, 1977), p. 255.
86. A review of inclusion-initiated laser damage in optical glass is given in R. W. Hopper and D. R. Uhlman, "Mechanism of Inclusion Damage in Laser Glass," *J. Appl. Phys.* **41**, 4023 (1970).
87. The 100 ps damage thresholds for 0.25 μ m light were obtained by T. Deaton and W. L. Smith at the Lawrence Livermore Laboratory, Livermore, CA. The 20 ns data were obtained by B. W. Newmann and D. H. Gill, "Ultraviolet Damage Resistance of Laser Coatings," in *Laser Induced Damage in Optical Materials* (NBS Special Publication 541, 1978), p. 100. The 1.0 μ m data were obtained by D. Milam, W. H. Lowdermilk, and F. Rainer at the Lawrence Livermore Laboratory, Livermore, CA (1979), and at 10 μ m by the Los Alamos Scientific Laboratory, Los Alamos, NM.
88. The damage thresholds for pulse durations of 0.1, 1.0, and 3.0 ns were measured at the Lawrence Livermore Laboratory, Livermore, CA by D. Milam, W. H. Lowdermilk, and F. Rainer. The damage thresholds at 30 ns were measured by N. Boling, G. Dube, and M. D. Crisp in *Laser Induced Damage in Optical Materials*, A. J. Glass and A. H. Guenther, Eds. (NBS Special Publication 387, 1974).
89. M. Bass and H. Barrett, "Avalanche Breakdown and the Probabilistic Nature of Laser-Induced Damage," *IEEE J. Quant. Elect.* **QE-8**, 338 (1972).
90. W. L. Smith, "Laser-Induced Breakdown in Optical Materials," *Opt. Eng.* **17**, 1353 (1971).
91. J. Maniscalco, J. Blink, R. Buntzen, J. Hovingh, W. Meier, M. Monsler, and P. Walker, *Civilian Applications of Laser Fusion*, Lawrence Livermore Laboratory, Livermore, CA, UCRL-52349, Rev. 1 (1978).
92. R. M. Feinberg, R. S. Lowder, and O. L. Zappa, *Low Pressure Laser Cavity for Repetitively Pulsed Electric Discharge Lasers*, Air Force Weapons Laboratory, Kirtland Air Force Base, NM, AFWL-TR-75-99 (1975).
93. S. N. Vlasov, V. A. Petrischer, and V. I. Talanov, "Averaged Description of Wave Beams in Linear and Nonlinear Media (The Method of Moments)," *Izv. Vuz., Radio Fiz.* **14**, 1353 (1971).

94. R. A. Haas and A. J. Glass, "Propagation of Laser Energy," *Laser Program Annual Report*, Lawrence Livermore Laboratory, Livermore, CA, UCRL-50021-77 (1978), pp. 716-720.
95. A. J. Glass, "Beam Transport Optics for Laser Fusion," *Soc. Phot. Instrum. Eng.* **121**, 111 (1977).
96. P. Jacquinot and B. Roizen-Dossier, "Apodization," *Prog. Opt.* **3**, 31 (1964).
97. B. C. Johnson, *Laser Program Annual Report*, Lawrence Livermore Laboratory, Livermore, CA, UCRL-50021-76 (1977), p. 2-322; UCRL-50021-74 (1975), p. 48.
98. A. J. Campillo, J. E. Pearson, S. L. Shapiro, and N. S. Terrell, Jr., "Fresnel Diffraction Effects in the Design of High-Power Laser Systems," *Appl. Phys. Lett.* **23**, 85 (1973).
99. J. T. Hunt, J. A. Glass, W. W. Simmons, and P. A. Renard, "Suppression of Self-Focusing Through Low-Pass Spatial Filtering and Relay Imaging," *Appl. Opt.* **17**, 2053 (1978).
100. The improvements in the performance of the Argus laser system are given by J. T. Hunt, "Argus Improvements," *Laser Program Annual Report*, Lawrence Livermore Laboratory, Livermore, CA, UCRL-50021-78 (1979), p. 2-133.
101. M. D. Crisp, N. L. Boling, and G. Dube, "Importance of Fresnel Reflections in Laser Surface Damage of Transparent Dielectrics," *Appl. Phys. Lett.* **21**, 364 (1972).
102. J. B. Trenholme, "The Ghost Focusing Code," *Laser Program Annual Report*, Lawrence Livermore Laboratory, Livermore, CA, UCRL-50021-75 (1976), p. 157.
103. The heuristic description of oscillator modes in this report follows that of D. Ross, Ref. 10, pp. 4-5.
104. A. G. Fox and T. Li, "Resonant Modes in a Maser Interferometer," *Bell Syst. Tech. J.* **40**, 453 (1961).
105. H. Kogelnik and T. Li, "Laser Beams and Resonators," *Proc. IEEE* **54**, 1312 (1966).
106. P. W. Smith, "Mode Selection in Laser," *Proc. IEEE* **60**, 422 (1972).
107. A. E. Siegman, Ref. 15, p. 293.
108. The oscillograms, streak camera pictures, and Fabry-Perot interferograms were provided by B. C. Johnson, Lawrence Livermore Laboratory, Livermore, CA.
109. P. W. Smith, "Mode-Locking of Lasers," *Proc. IEEE* **58**, 1312 (1970).
110. D. J. Kuizenga and A. E. Siegman, "FM and AM Mode-Locking of the Homogeneous Laser—Parts I & II," *IEEE J. Quant. Elect.* **QE-6**, 673 (1970).
111. A. E. Siegman and D. J. Kuizenga, "Active Mode-Coupling Phenomena in Pulsed and Continuous Lasers," *Opt. Elect.* **6**, 63 (1974).
112. *Laser Program Annual Report*, Lawrence Livermore Laboratory, Livermore, CA, UCRL-50021-77 (1978), p. 2-210; and UCRL-50021-78 (1979).
113. W. E. Martin, B. C. Johnson, and K. R. Guinn, "Pulse Shaping for Laser Fusion," in *IEEE/OSA Conf. on Laser Engineering and Application*, Washington, D.C., 1977, p. 53.
114. D. J. Kuizenga and W. E. Martin, "Argus Oscillator and Pulse Stacker," *Laser Program Annual Report*, Lawrence Livermore Laboratory, Livermore, CA, UCRL-50021-77 (1978), p. 2-219.
115. These examples of coherent pulse shortening and stretching were obtained by J. E. Murray. For details see *Laser Program Annual Report*, Lawrence Livermore Laboratory, Livermore, CA, UCRL-50021-77 (1978), p. 2-210; and UCRL-50021-78 (1979), p. 7-11.
116. C. Brecher, L. A. Risenberg, and M. J. Weber, "Line-Narrowed Fluorescence Spectra and Site-Dependent Transition Probabilities of Nd^{3+} in Oxide and Fluoride Glasses," *Phys. Rev. B* **18**, 5799 (1978).
117. J. C. Almasi, J. P. Chernock, W. S. Martin, and K. Tomiyasu, "Face Pumped Laser," *General Electric Report to the Office of Naval Research*, AD-467 468/5 ST (May 1966).
118. J. E. Swain, R. E. Kidder, K. Pettipiece, F. Rainer, E. D. Baird, and B. Loth, "Large-Aperture Disk Laser System," *J. Appl. Phys.* **40**, 3973 (1969).
119. W. Koechner, *Solid State Laser Engineering* (Springer-Verlag, NY, 1976).
120. G. J. Linford, R. A. Saroyan, J. B. Trenholme, and M. J. Weber, "Measurements and Modeling of Gain Coefficients for Neodymium Laser Glasses," *IEEE J. Quant. Elect.* **QE-15**, 510 (1979).
121. A. J. Beaulieu, "Transversely Excited Atmospheric Pressure CO_2 Lasers," *Appl. Phys. Lett.* **16**, 504 (1970).

122. R. Dumanchin and J. Rocca-Serra, "Augmentation de L'energie et de la Puissance Fournie Par Unite de Volume dans un Laser a CO₂ en Regime Pulse," *Compt. Rend. Acad. Sci.* **269** (1969).
123. J. D. Daugherty, E. R. Pugh, and D. H. Douglas-Hamilton, "A Stable, Scalable High Pressure Gas Discharge as Applied to the High Pressure CO₂ Laser," *Bull. Am. Phys. Soc.* **17**, 399 (1972).
124. C. A. Fenstermacher, M. J. Winter, W. T. Leland, and K. Boyer, "Electron Beam Controlled Electrical Discharge as a Method of Pumping Large Volumes of CO₂ Laser Media at High Pressure," *Appl. Phys. Lett.* **20**, 56 (1972).
125. N. G. Basov, "Gas Lasers at High Pressures," *JETP Lett.* **14**, 285 (1971).
126. For a review see J. D. Daugherty, "Electron Beam Ionized Lasers," in *Principles of Laser Plasma*, G. Bekefe, Ed. (John Wiley & Sons, NY, 1976), p. 369.
127. J. M. Auerbach, N. C. Holmes, J. T. Hunt, and G. J. Linford, "Closure Phenomena in Pinholes Irradiated by Nd Laser Pulses," *Appl. Opt.* **18**, 2495 (1979).
128. L. J. Aplet and J. W. Carson, "A Faraday Effect Optical Isolator," *Appl. Opt.* **3**, 544 (1974).
129. K. Eidman, P. Sachsenmaier, H. Salzmann, and R. Sigel, "Optical Isolators for High Power Giant Pulse Lasers," *J. Phys.* **E 5**, 56 (1972).
130. For a review and history of electro-optic switches see I. P. Kaminow, *An Introduction to Electro-Optic Devices* (Academic Press, NY, 1974).
131. M. A. Summers and B. C. Johnson, *Design and Performance of Large Aperture KD*P Pockels Cells*, Lawrence Livermore Laboratory, Livermore, CA, UCRL-79952 (1977).
132. M. J. Weber, "Optical Materials for Neodymium Fusion Lasers," reprinted from *Critical Materials Problems in Energy Production* (Academic Press, NY, 1976), p. 261.
133. For detailed descriptions of laser and target optical diagnostics, see the *Annual Reports* from the laboratories involved in laser plasma interaction work. These laboratories include: CEA Limeil, France; KMS Fusion, Inc., Ann Arbor, MI; Naval Research Laboratory, Washington, DC; Osaka University, Osaka, Japan; Sandia Laboratories, Albuquerque, NM; the Lebedev Institute, Moscow, USSR; the Max Planck Institute for Plasma Physics, Garching, Germany; the Rutherford Laboratory, Didcot, England; Lawrence Livermore Laboratory, Livermore, CA; Los Alamos Scientific Laboratory, Los Alamos, NM; University of Rochester, Laboratory for Laser Energetics, Rochester, NY.
134. The diagnostic techniques used to verify the initial beam-target relationship in the Livermore Laser Program were reviewed in the *Laser Program Annual Report*, Lawrence Livermore Laboratory, Livermore, CA, UCRL-50021-75 (1976), p. 369.
135. In a laser system operating safely within its propagation limits, and in which the amplifiers are uniformly pumped, a "square-profile" laser pulse and a low-level cw laser beam will propagate in virtually an identical manner. However, if the amplifier pumping characteristics are significantly nonuniform, then thermal lensing will occur due to nonuniform heat deposition, and the focal properties of the pulsed beam will differ from those of the cw alignment beam. Examples of pump-induced distortion are found in G. J. Linford, H. H. Chau, J. A. Glaze, C. B. Layne, and F. Rainer, "Pump-Induced Optical Distortions in Disk Amplifier Modules: Holographic and Interferometric Measurements," *Appl. Opt.* **14**, 3057 (1975).
136. J. Petruzzi and C. E. Violet, *Positioning Alignment Balls at the Focal Point of a Lens. I: Preliminary Measurements*, Lawrence Livermore Laboratory, Livermore, CA, UCRL-749 (1974); and C. E. Violet and J. Petruzzi, *Positioning Alignment Balls at the Focal Point of a Lens. II: Two Beam Mock Up*, Lawrence Livermore Laboratory, Livermore, CA, UCRL-859 (1975).
137. J. B. Trenholme, E. S. Bliss, J. L. Emmett, J. A. Glaze, T. J. Gilmartin, R. O. Godwin, W. F. Hagen, J. F. Holzrichter, G. J. Linford, W. W. Simmons, and D. R. Speck, "Fusion Laser Development at the Lawrence Livermore Laboratory," in *Laser Interactions and Related Plasma Phenomena*, J. Schwartz and H. Hora, Eds. (Plenum Press, NY, 1977), Vol. 4A, p. 1.
138. N. G. Basov, O. N. Krokhin, Yu. A. Mikhailov, G. V. Sklizkov, and S. I. Fedotov, "Powerful 12-Channel Laser Installation 'Delfin' for Spherical Heating of Thermonuclear Targets," in *Laser Interaction and Related Plasma Phenomena*, *ibid.*

139. W. Seka, J. Soures, O. Lewis, J. Bunkenberg, D. Brown, S. Jacobs, G. Mourou, and J. Zimmerman, "Design and Performance Characteristics of a High Power Phosphate Glass Laser System," *Appl. Opt.* **19**, 3 (1980), pp. 409-419, also available as *Laboratory for Laser Energetics Report 90*, University of Rochester, Rochester, NY.
140. S. Singer, "CO₂ Laser Systems for Fusion Experiments," in *Laser Interactions and Related Plasma Phenomena* (Plenum Press, NY, 1977), Vol. 4A, p. 121.
141. T. F. Stratton, "CO₂ Short-Pulse Laser Technology," in *Lectures on High Power Gas Lasers at International College of Applied Physics on Capri, September 1975* (Institute of Physics, London, Inst. Phys. Conf. Ser. No. 29, E. R. Pike, Ed., 1976), p. 284.
142. The ideas for multipass-laser-system architecture have been present for many years. One of the earliest examples was the long-path laser constructed at the Lawrence Livermore Laboratory in 1965-68. A description can be found in S. W. Mead, R. E. Kidder, J. E. Swain, F. Rainer, and J. Patruzzi, "Preliminary Measurements of X-ray and Neutron Emission from Laser Produced Plasmas," *Appl. Opt.* **11**, 345 (1972). It was not completely successful because the very long propagation paths led to severe beam distortion. Relay imaging and better understanding of self-focusing make these systems feasible today. For a review of recent ideas on multipass systems, see *CP&D Interim Report - Shiva Nova*, T. J. Gilmartin and C. W. Meier, Eds., Lawrence Livermore Laboratory, Livermore, CA, Misc. Report 107 (1977), pp. 2-161.
143. W. F. Hagen, "Multipass Laser Systems—Analysis and Optimization," *Laser Program Annual Report*, Lawrence Livermore Laboratory, Livermore, CA, UCRL-50021-77 (1978), p. 2-224.
144. This geometry has been employed on the laser systems at KMS Fusion, Inc., Ann Arbor, MI.
145. M. D. Montgomery, R. L. Carlson, D. E. Casperson, S. J. Czuehlewski, J. F. Figreira, R. F. Haglund Jr., J. S. Ladish, A. V. Nowak, and S. Singer, "Stabilization of High-Gain Multipass Power Amplifiers Using Saturable Absorbers: Experience on the LASL Eight Beam System," *Appl. Phys. Lett.* **32**, 324 (1978).
146. The optimization of Nd:laser systems to obtain the greatest performance/dollar cost is described in the *Laser Program Annual Report*, Lawrence Livermore Laboratory, Livermore, CA, UCRL-50021-74 to 78 (1975-1979). For a concise review of glass-laser optimization, see the article by J. B. Trenholme et al., "Laser System Design—Shiva Nova," in *Nova*, T. J. Gilmartin and C. W. Meier, Eds., Lawrence Livermore Laboratory, Livermore, CA, Misc. Report 107 (1977).
147. The isofluence laser concept is reviewed in the *Nova CP&D Reports*, Lawrence Livermore Laboratory, Livermore, CA, Misc. Reports 2242 (1976), 107 (1977), and 111 (1978).
148. The costs of Nd:glass laser system components are reviewed in the *Nova CP&D Reports*, *ibid.*
149. J. L. Emmett, "Approaches to Extremely High-Power Laser Systems," in *Topical Meeting on Inertial Confinement Fusion, Feb. 7-9, 1978, San Diego, CA*.