Lawrence Livermore Laboratory

STATUS OF LARGE NEODYMIUM GLASS LASERS

James A. Glaze, William W. Simmons and Wilhelm F. Hagen

March 15, 1976

MASTER

This Paper was Prepared for Submission to the
Society of Photo-Optical Instrumentation Engineers

SPIE Meeting, Reston, VA March 22-23, 1976

This is a preprint of a paper intended for publication in a journal or proceedings. Since changes may be made before publication, this preprint is made available with the understanding that it will not be cited or reproduced without the permission of the author.

STATUS OF LARGE NEODYMIUM GLASS LASERS*

James A. Glaze, William N. Simmons and Wilhelm F. Hagen
Laser Fusion Division, Lawrence Livermore Laboratory
Livermore, California 94550

NOTICE
This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

Introduction

The Nd:Glass laser is used extensively throughout the world for laser fusion and laser plasma interaction studies. Its popularity, to a large extent, stems from the fact that it is capable of operating reliably in the subnanosecond-terawatt power regime. In addition, the technology necessary to combine a large number of laser chains to produce a system capable of multi-terawatt performance currently exists and is being applied.

At the Lawrence Livermore Laboratory two large laser systems are currently in operation and two are under construction. The JANUS and CYCLOPS systems produce 0.5 and 1 terawatt of focusable power in 0.1 ns respectively. These systems are being used for target irradiation and beam propagation experiments and provide our basic test beds for laser component and system development. The ARGUS laser is a two arm, 3 terawatt system dedicated to fusion target irradiation experiments. This system is scheduled for initial operation in March, 1976. The SHIVA system which is scheduled for early testing in mid-1977, is a 20-arm system designed to operate at 20-30 terawatts. This system is designed to demonstrate significant thermonuclear burn from the isentropic compression of D-T targets. In addition to these systems, various system upgrades are currently being evaluated. Figure 1 is a graphical presentation of the LLL Nd:Glass laser development program; the ordinate gives the anticipated TN fuel pellet gain that can be achieved with each system. The shaded areas refer to the performance of system upgrades which, to date, have not been funded. In this paper the elements of a Nd:Glass laser chain as it is constructed for fusion experiments are described. Also presented is a brief overview of the ARGUS and SHIVA systems. For a discussion of the JANUS and CYCLOPS lasers, the reader is referred to the 1974 LLL Laser Program Annual Report (UCRL-50021-74) and to the review article of Reference 11.

LASER FUSION ENERGY YIELD PROJECTIONS

Fig. 1. Schematic presentation of the Nd:Glass laser development program at Livermore. The ordinate gives the anticipated TN fuel pellet gain that can be achieved with each system. The shaded regions refer to the performance of system upgrades which have not been funded to date. The ARGUS II and SHIVA systems are discussed in this paper.

*This work was performed under the auspices of the U.S. Energy Research and Development Administration. Contract Number W-7405-Eng-48.

Laser Chain Description

In discussing the makeup of a Nd:Glass laser system for use in target irradiation experiments, it is useful to consider a block diagram of a single laser chain. Figure 2 shows such a diagram for a chain comprised of both rod and disk amplifiers. Below we discuss the various components shown in this diagram.

BLOCK DIAGRAM FOR A Nd:GLASS LASER CHAIN

Fig. 2. Block diagram of a typical Nd:Glass laser chain as it would be staged for laser fusion experiments. A disk amplifier group is also shown. Such a group may contain several amplifier heads; these heads would generally have the same clear aperture. The rod amplifier groups are staged in a similar manner.

The master oscillator used at LLL is a Nd:YAG laser passively mode locked with a flowing bleachable dye. Bandwidth is established with an etalon whose temperature is maintained within $\pm 0.1^\circ\text{C}$ with a closed cycle coolant loop. Uniform pumping of the rod is achieved with an afocal double ellipsoid reflector geometry. The oscillator output consists of a train of subnanosecond pulses, one of which is selected and switched out for injection into the preamplifier stages. Energy of the largest pulse in the train is typically 2 nJ. Because of the statistical manner in which the dye is bleached by fluorescent noise spikes, this oscillator does not have the pulse-to-pulse temporal stability that is desired for large system applications. (Variations of up to 30% are sometimes observed). Attempts are currently being made to develop oscillators with improved longitudinal mode discrimination. One promising approach uses a synchronously driven intracavity loss modulator (fast Pockels' cell) in addition to the dye cell.⁽¹⁾ Transform limited pulses ranging from <50 psec to >5 nsec have been achieved. This oscillator to date, however, has problems of pulse train instability thought to arise from improper impedance matching of the PFM and Pockels' cell.

The oscillator pulse switchout incorporates a fast Pockels' cell (1 cm diameter) positioned between crossed polarizers. In early designs half-wave voltage was applied to the cell by switching a high-pressure N_2 -filled spark gap with optical energy derived from the early portion of the pulse train. Since the optical energy arrives at the spark gap in the form of pulses whose spacing (typically 10 ns) is long compared to gap break-down times, it is possible to adjust the gas pressure so that the state of ionization required for full avalanche breakdown across the gap is achieved just prior to the arrival at the Pockels' cell of the pulse selected for switchout. This scheme is widely used, but suffers from jitter in the gap break-down time, resulting in part from shot-to-shot variability of the pulse train amplitude and in part from electrode degradation with time. More recently, modern electronic switches have eliminated the troublesome spark gap entirely.⁽²⁾ In the electronic switchout circuit in present use at LLL, a krytron[®] switch, activated by an avalanche transistor stack, discharges a stripline circuit which is accurately impedance matched to the Pockels' cell. This circuit derives its timing signal from the pulse train through a vacuum photo-diode and voltage-settable tunnel diode comparator. By careful adjustment of time delay and threshold voltage, switch-out pulse energy variation can be minimized.

The pulse shaper is a device that transforms the temporally gaussian oscillator pulse to a pulse more suitable for target irradiation. Theoretical calculations show that the desired waveform is a function of target size, composition, and available laser energy.⁽³⁾ Of all the components that comprise the chain, this one, to date, is least clearly defined in terms of performance requirements and construction. However, a large number of schemes have been proposed; these can be broadly characterized as pulse stackers, shutters and active shapers. The stacker produces a composite pulse derived from a single short pulse that is suitably delayed and attenuated. A patented scheme using a double etalon is presently in use at KMS Fusion.⁽⁴⁾ Another scheme uses a Faraday rotator placed between cross polarizers.⁽⁵⁾ Successive reflections from the

*Registered Trademark name.

rotator surfaces experience different rotations and hence different transmissions through the output polarizer. This device, while simple to implement, does not provide an exponentially increasing signal as does the RMS stacker. Optical shutters have been in use for some time. In this scheme a Pockels' or Kerr cell modulator is used to chop-out a portion of a longer Q-switched pulse. Bandwidth limitations on the modulator presently limit pulse rise time to about 150 psec. Furthermore, all shutters are limited by an intrinsic dynamic amplitude range of 30-40 dB. Active shapers rely on the transmission properties of saturable absorbers. One example is that proposed by Elliott and Massey. (6) In their scheme a series of dye cells are optically gated with combinations of exponential and gaussian pulses suitably delayed in time. Their calculations predict that the pulse shape discussed in Reference 3 can be closely matched.

Laser radiance is limited by both linear and nonlinear wavefront distortions. Static aberrations arising from surface figure error can be as high as 0.4 waves RMS for a laser such as CYCLOPS which has over 150 optical surfaces. Quasistatic aberrations arising from flashlamp-induced thermal distortion of laser disks can be several waves unless elaborate cooling procedures are adopted. Adjustable corrections of several waves can be made with simple refractive elements. (7) Astigmatism, for example, can be eliminated with an adjustable pair of coaxial cylindrical lenses. Coma, spherical aberration and wavefront tilt can be compensated in a similar manner. While this technique is limited to the Seidel aberrations, it is cost effective and amenable to integration into a large system. Adaptive optics such as deformable mirrors or phased arrays may someday be developed for fusion laser applications. At the present time such devices seem too costly and complex for use in large systems.

In addition to small-scale self-focusing both whole-beam self-focusing and diffraction can degrade beam focusability. To ameliorate these effects a beam shaping transmission filter (apodizing aperture) is placed at the beginning of the first power amplifier stage. Since the rate at which the phase is retarded by the nonlinear interaction is proportional to the intensity, the beam profile will have a profound effect on the intermediate and far-field phase and intensity distributions of the focused beam. For a circular beam with a parabolic intensity profile, the phase retardation of course will be parabolic and will behave as if it has passed through a weak positive lens whose focal length changes in time with the pulse. When the beam is brought to a focus, this lensing will cause a time varying shift of the focal plane. For a system such as CYCLOPS, operating at a terawatt and using an $f/2.5$ focusing lens, this shift can be as large as 100 microns. Other beam profiles give rise to far more complex focal plane behavior; therefore the parabolic shape is preferred for many applications. Because of diffraction, a simple parabolic profile will not propagate through the chain without developing near-field Fresnel ripples. To avoid this, a transmission filter which is parabolic over the central portion of the aperture but decreases smoothly to zero at the edge is used. In choosing the size and location of the apodizing aperture, one must be careful that diffraction ripples, which can be further amplified by self-focusing, are minimized, while at the same time amplifier apertures are optimally filled by the beam for maximum power extraction.

For fusion targets, amplified spontaneous emission (ASE) must be attenuated to avoid target damage prior to the arrival of the compressing pulse. Experiments have shown that energy densities as low as 6 J/cm^2 will cause damage to plastic parts and glue joints. (8) Although it is difficult to pinpoint a precise design goal for control of ASE, it is currently thought that the output from each chain must be less than 500 mJ. A number of techniques can be used to attenuate ASE; examples include Pockels' cells, fast Faraday rotators, dye cells, chopper wheels, and combinations of these elements. Pockels' cells up to 25 mm in diameter are in routine use today. Cells up to 50 mm in diameter and having 10 nsec shutter speeds are currently being designed for use on the ARGUS and SHIVA systems. Dye cell isolators, while available in all aperture sizes, are undesirable because of large insertion losses (30%-40%) even at high power densities. In addition, they contribute to beam degradation because of their large non-linear index of refraction. Fast Faraday rotators currently look promising. It is believed that rotators up to 200 mm in diameter with less than 4 nsec shutter speeds are feasible. (9)

Damage to laser fusion targets can also be caused by precursor pulses from the oscillator. Measurements on glass microfibers have shown that 100 ps pulses with energy as low as 100 microjoules can cause damage to glue joints. (5) If, for example, the target is to be irradiated with a 100 joule compression pulse, it would be necessary to provide 60 dB of prepulse isolation. There are several sources of oscillator prepulse that can be readily identified. The first is simply leakage through the Pockels' cell-polarizer switchout. This leakage can generally be kept below 40 dB with good multilayer dielectric polarizers providing the contrast ratio of the Pockels' cell is $> 40 \text{ dB}$; such Pockels' cells are available. A second source is inter-pulse noise; this of course is not attenuated during the open time of the switchout. Fortunately it is typically down in intensity (relative to the desired pulse) by 30-40 dB. Prepulse from switchout jitter arises when the shutter admits a portion of the pulse preceding the pulse selected for switchout. This source has been substantially eliminated, however, with modern electronic switchouts. In summary, about 30 dB of additional isolation is required. This can be obtained with small dye cells following early pre-amplifier stages.

In staging a laser chain for maximum focusable output power it is convenient to consider what is called an amplifier group. Such a group is shown in the inset of Figure 2 and is comprised of isolation and amplifier stages positioned between spatial filters. The isolation stage is composed of a Faraday rotator and polarizer; it protects the chain from laser energy reflected from the target. The spatial filters are used to remove beam filaments and spatial noise exacerbated by small scale self-focusing. These devices are typically constructed from a pair of aspherized $f/10$ lenses with a 300 micron diameter diamond pinhole positioned at lens focus. They are pumped to a hard vacuum to minimize breakdown effects. Such a filter has a spatial bandpass of about 9 cm^{-1} ; this is sufficient to pass the whole-beam while stripping higher frequencies from it. The staging methodology for designing a given amplifier group has been given a great deal of attention at LLL and is discussed in several articles. (10) (11).

The ARGUS and SHIVA Systems

The ARGUS laser is a two-arm system with 20 cm final amplifier apertures, and is capable of delivering more than 3 TW of focusable power to targets with diameters of a few hundred microns. This capability is planned to be upgraded in the near future. Here we describe the physical characteristics of the laser and associated facility, and some of the important components incorporated therein.

Functionally, the laser system consists of a mode-locked Nd:YAG oscillator and pulse selector, followed by three 12 mm aperture rod amplifiers; beam profiling, collimating, and splitting optics; and in each arm, three 2.5 cm x 25 cm rod amplifiers, one 4 cm x 25 cm rod amplifier, three 6-disk 8.5 cm C.A. disk amplifiers, and four 3-disk 20 cm C.A. disk amplifiers. A schematic view of the beam profile as it traverses key chain components is shown in Figure 3. Isolation (elements not shown) against prepulse, prelate and backward propagation are accomplished with a suitable combination of dye cells, Pockels' cells, and Faraday isolators. Also shown is the beam diameter through successive stages, nominal beam power (rated at 100 psec) at the entrance to each spatial filter, and bank energy required for each of the amplifier stages shown. Multiple vacuum spatial filters (5 in each arm) are employed at strategic intervals along each chain to control the growth of small scale beam break-up, and to serve as beam expansion telescopes. The spatial filters employ f/10 aspheric lenses, diamond wire die pinholes, and ion pump evacuation to residual pressures less than 10^{-6} torr.

ARGUS LASER SYSTEM, SINGLE ARM, 12/23/75

Fig. 3. Optical profile of a single ARGUS laser chain. Representative values are given for the laser energy and power at each amplifier stage. Also shown are the clear apertures of each amplifier, the electrical energy supplied to the flashlamps, and typical whole beam nonlinear phase retardation as it accumulates in each amplifier stage.

Chain design and spatial filter placement is guided by the following criteria: (1) The incremental small-scale beam breakup integral, $\Delta B = \int_{\Delta} |\delta I| dI$, between successive spatial filters shall not exceed an upper bound (typically 2.5-3.0); (2) the final amplifier stage shall be driven to the highest flux allowed consistent with criterion (1). Nominal values of ΔB and whole-beam nonlinear phase retardation Φ are also shown in Figure 3. By employing state-of-the-art optical components, which present a minimum of glass path length to the beam, Φ is further minimized.

The energy storage system consists of approximately 3 capacitor banks. For reduced cost and complexity and increased reliability, individual PFN modules (18 kJ driving one series lamp pair) are charged in 1.2 MJ blocks and switched in 600 kJ blocks. Lamp ignition is effected by a controlled overvoltage ring-up during the first few microseconds of the discharge. To detect incipient flashlamp failure prior to a laser shot, an auxiliary charge-and-fire-system provides all disk amplifier lamps with a low energy discharge, inter-opts discharge parameters, and displays to the operator the condition of each lamp pair.

A photograph of the ARGUS laser in partial construction (Figure 4) illustrates the general system layout. In the near foreground are the 25-cm aperture rod amplifier chassis; along the center table are located oscillator no. 1, the switchout unit, and associated small optics; along each arm various disk amplifiers, spatial filters, and isolator units; the rack in the center contains the oscillator control units, spatial

filter vacuum pump power supplies, PLC display panels, and a variety of cable patch junctions; and along the far wall, the H_2 cooling gas flow control.

An optical schematic of a SHIVA laser chain is shown in Figure 5. The nominal focusable power from this chain is expected to be about 1.4 terawatts. While performing about as well as an ARGUS chain, this chain is considerably more cost effective. The cost savings arise because the final 20 cm aperture δ power amplifier group is driven by the smaller 15 cm γ amplifier. This of course requires an additional spatial filter in the driver section. The staging of the SHIVA chain represents our latest thinking on how to minimize both whole-beam and small-scale self-focusing while maximizing the focusable power per unit cost.

Fig. 4. View of the ARGUS laser system in partial construction. The target chamber and beam turning optics are located behind the far wall.

The SHIVA system which has been described in several reports and publications^(12,13) is comprised of 20 chains. These will be mounted in columns of 5 on a support structure (space frame) constructed from steel tubing.⁽¹⁴⁾ Figure 6 shows a scale drawing of the laser and target space frames as they appear in the bay of the High Energy Laser Facility at Livermore. In this figure an icosahedral geometry is shown for bringing the beams onto the target.

Figure 7 shows a plan view of the laser chain. Of particular interest is the electro-optical beam alignment system. This system can be divided into five parts whose functions include oscillator alignment, main chain pointing, beam centering on the final focusing lens and pointing and focusing of the beam onto the target. The purpose of the oscillator alignment system is to maintain collinearity of the master oscillator and a cw alignment laser. This is achieved with 5-axis mirrors at the output of each oscillator. These mirrors are controlled by servo-loops between the mirror axis and pointing and centering sensors located in the preamplifier stage. Since corner sensors are used to control both mirrors, collinearity is assumed as long as detector responses are linear for both the pulsed and cw mode. It is required that the relative angular accuracy of these two beams be about ± 2 microradians.

SHIVA LASER CHAIN

Fig. 5. Optical profile of a single SHIVA laser chain. Representative values are given for the laser energy and power at each amplifier stage. Also shown is the clear aperture of each amplifier and the electrical energy supplied to the flashlamps.

SHIVA SPACE FRAME

Fig. 6. Mechanical support structure for the laser and target sections. The laser frame is capable of supporting some 600 individual component assemblies and maintaining a tolerance of ± 4 μ rad between any two points over a period of 100 s. The target frame supports the target chamber, turning mirrors and the PFC sensors.

The purpose of the main-chain pointing system is to provide an angular correction at the apodizing aperture for errors incurred in the beam splitter array. This is accomplished with a 2-axis angle gimbal placed in front of the apodizing aperture and a pointing sensor placed immediately after the aperture (this sensor is not shown in Figure 6). Pointing accuracies of ± 100 microradians are required to keep the beam centered in the main chain spatial filters. The angle gimbal is part of the same mirror assembly that is used for optical path length adjustment.

References

1. B. C. Johnson and W. D. Fountain, An Active/Passive Mode-Locked Laser Oscillator, Technical Digest, p. 322, International Electron Devices Meeting, 1974, Washington, D.C.
2. D. W. Phillion, Private Communication.
3. J. H. Nuckolls, J. L. Emmett and L. L. Wood, Laser-Induced Thermonuclear Fusion, Physics Today, August, 1973.
4. C. E. Thomas and L. D. Siebert, Appl. Optics, 15, 462, (1976).
5. G. E. Somargren, Private Communication.
6. R. A. Elliott and G. A. Masse, Pulse Shaping with Saturable Absorbers, Technical Digest, p. 314, International Electron Devices Meeting, 1974, Washington, D.C.
7. R. A. Buchroeder and R. B. Hooker, Appl. Optics, 14, 2476, (1975).
8. J. F. Holzfichter, D. R. Speck, and J. E. Swain, Meeting of the American Physical Society, Albuquerque, N.M. Mexico, October 28-31, 1974.
9. W. L. Gagnon, Private Communication.
10. J. B. Trenholme, Optics in Laser Fusion, Proceedings of the Society of Photo-Optical Instrumentation Engineers, Vol. 69, Laser Systems, p. 158, (1975).
11. J. A. Glaze, High Energy Glass Lasers, Proceedings of the Society of Photo-Optical Instrumentation Engineers, Vol. 69, Laser Systems, p. 45, (1975).
12. Laser Program Annual Report, UCRL-50021-74, pp. 68-123, (1974), Lawrence Livermore Laboratory.
13. T. J. Gilman, R. C. Godwin, J. W. Davis, M. F. Hagen, C. H. Hurley, G. W. Leppelmeier, G. J. Linford, J. O. Myall, W. C. O'Neal, and J. B. Trenholme, 10 Kilojoule SHIVA Laser System for Fusion Experiments at LL, 1975 IEEE/OSA Conference on Laser Engineering and Applications, May 28-30, 1975.
14. C. A. Hurley and J. O. Myall, High Stability Space Frame for a Large Fusion Laser, Sixth Symposium on Engineering Problems of Fusion Research, Nov. 17-21, 1975.