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LAWRENCE LIVERMORE LABORATORY
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THE LAWRENCE LIVERMORE LASER FUSION PROGRAM: A STATUS REPORT

William F. Krupke

April 15, 1975

Third Conference on the Laser
The New York Academy of Sciences
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MASTER

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STATUS OF THE LASER FUSION PROGRAM AT LLL *

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The Laser Fusion Program at the Lawrence Livermore Laboratory is presently emerging from a three-year period of intensive development of the tools required for significant DT implosion experiments of continuously increasing scale. These diverse tools include target design codes, sophisticated target fabrication techniques, radically new diagnostics instrumentation, high peak-power-high brightness laser technology, and fully integrated laser-target-diagnostic irradiation facilities. These tools have recently led to the successful production of neutrons from compressed DT-containing targets together with a wealth of correlating plasma physics data. The current status of major program activities at LLL will be reviewed and major future milestones will be projected.

This paper prepared for Third Conference on the Laser, New York Academy of Sciences, April 22-25, 1975.

*This work was performed under the auspices of the United States Energy Research & Development Administration.

THE LAWRENCE LIVERMORE LASER FUSION PROGRAM: A STATUS REPORT*

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INTRODUCTION

The Laser Fusion Program conducted by the Lawrence Livermore Laboratory (LLL) represents approximately half of the U.S. Energy Research and Development Administration's (ERDA) effort toward the achievement of thermonuclear (TN) fusion via inertial confinement. The scientific rationale and operational elements of the present LLL program are rooted in the conceptual notions of inertial confinement fusion by a laser-driven implosion of deuterium-tritium (DT) fuel, advanced by Nuckolls¹ and by Kidder.² Extensive theoretical and numerical computational studies of relevant implosion processes were conducted at LLL through the 1960's. The results of these studies, coupled with the rapidly developing high-energy laser technology, prompted a significant scaling up of the LLL Laser Fusion Program in the late 1960's to its present direct manpower level of 230. The LLL program is presently emerging from a three-year period of intensive development of the tools required for significant DT implosion experiments of continuously increasing scale. These diverse tools include expanded target design codes (encompassing the fluid mechanics of high-density, high temperature plasmas, radiation transport, TN-burn

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physics, and laser-plasma coupling), sophisticated target fabrication techniques, radically new diagnostics instrumentation and techniques, high peak-power, high brightness laser technology, and fully integrated laser/target/diagnostics irradiation facilities. The successful development of these tools has led recently to the production of neutrons from compressed DT-containing targets, together with a wealth of correlating plasma physics data.

My presentation today takes the form of a status report on the program activities alluded to above. It is again to develop a sense of the critical interplay between the various program elements and to highlight major advances. Although admittedly speculative, major program milestones over the next few years will be ventured, based on recent experimental and theoretical results.

TARGET DESIGN

Theoretical considerations of the relevant physics of a laser-driven implosion confirm that the T₉₂ yield will depend on many parameters of the irradiation field. The most important parameters include laser energy, wavelength, peak power density, temporal shape of the pulse, and the temporal and spatial symmetry of target irradiation. It is expected that pellets designed to operate at lower laser energies will be most sensitive to these irradiation parameters. In order to efficiently utilize present resources in the development of programmatically useful laser irradiation sources and diagnostics instrumentation, the multi-dimensional parameter space of target design is being explored with a sophisticated computer program called LASNEX, which simulates laser implosions and fusion micro-explosions. LASNEX is a Lagrangian hydrodynamic code which includes:

- treatment of strong shocks via modeling of viscosity
- flux-dependent electron and ion thermal conduction
- classical and anomalous absorption of laser light
- generation and transport of energetic, non-Maxwellian electrons
- multi-frequency transport of x-radiation
- effect of self-generated magnetic fields on hydrodynamic motion and thermal conduction
- thermonuclear burn

During this past year, the LASNEX code was improved with the addition of a ray trace physics package to treat refraction of the laser beam; a multi energy group fusion ion and neutron transport physics package was added to improve the accuracy of calculating fusion micro-explosions at high density-radius products; and a physics package was also added to treat inhibition of electron transport by plasma instabilities when the electron temperature greatly exceeds the ion temperature.

The LASNEX computer code has been used to design a multitude of target types. The simplest of these is the so-called "pl" or pusher type shown in Figure 1. The target consists of a glass shell, filled with low density DT, mounted on a stalk. A structural cross-section of such a micro-capsule is shown at the left; an LLL fabricated target is shown at the right. Upon coupling of laser energy to the glass shell, the radially heated shell (pusher) explodes. The inward moving portion of the shell compresses the DT fuel to nearly the original pusher density ($\sim 1 \text{ g/cc}$) and heats the compressed region to temperatures near 1 keV. Thermonuclear self-heating is insignificant because the product of core density and core radius (ρR) is so small, typically 10^{-4} to 10^{-3} g/cm^2 and because the TH burn

efficiency is so small ($\sim 10^{-6}$). Figure 2 shows a series of calculations for the gains of optimized exploding pusher targets as a function of absorbed energy. This graph shows that laser energies (and peak powers) well beyond the projected state-of-the-art will be required to achieve light breakeven using exploding pusher type targets. The exploding pusher implosion differs significantly from the high density implosions which must be achieved for fusion power applications. In the high density, isentropic implosion, R is sufficiently large ($\sim 1 \text{ gm/cm}^2$) so that thermonuclear self-heating is significant. In the isentropic implosion, the shell is not exploded but is gently pushed radially inward by just the ionization heating of the laser pulse to suppress fluid instabilities and to minimize entropy changes so that high densities ($\sim 1000 \text{ gm/cm}^3$) may be achieved. The plot of T_h yield versus laser energy (or peak power) for high density implosions (Figure 2) indicates that these targets will not perform well below a kilojoule of laser energy. Early experiments have therefore been conducted with the exploding pusher type targets which perform relatively well at the low laser energies available today.

Target designs using LASNEX, which are far from complete, indicate that a set of laser parameters which will enable scientific breakeven (T_h energy = light energy) to be approached are: energy 5-10 kJ, peak power 20 TW, pulse shape an optimum sequence of 5-10 square pulses, precursors ≤ 1 millijoule, wavelength 0.5-1.0 μm , angle of incidence ≤ 20 degrees to surface normal and symmetric 10 pscc temporally and $\sim 10^\circ$ spatially over angles of about 30° degrees. The corresponding requirements for a lower performance pellet capable of reaching one per cent of scientific breakeven are: energy 5-10 kJ, peak power 10 TW, pulse shape Gaussian, precursors ≤ 1 millijoule, wavelength 1 μm , angle of incidence ≤ 20 degrees, and symmetry 100 pscc temporally and $\sim 30^\circ$ spatially.

SOLID STATE LASER FACILITY

In fiscal year 1973, the Lawrence Livermore Laboratory was assigned program responsibility for the design, construction, and operation of a high energy laser facility (HELFF), as a S25M line item. This facility will consist of three principle systems -- the SHIVA laser, a target handling and irradiation chamber, and a diagnostics array -- integrated together to explore the basic physical processes of inertial confinement fusion and achieve the early milestones of ERDA's Laser Fusion Program. The neodymium glass laser medium has been selected for the facility because of its relatively advanced state of technology and its relatively short wavelength. The SHIVA laser is being designed to deliver 20 terawatts peak power and up to 10 kilojoules per pulse on target at a wavelength of 1.06 microns. The multi-arm laser configuration will permit spherically symmetric irradiation of the targets. Laser pulses with widths varying between 20 psec and 20 nsec (with correspondingly scaled pulse energies) will be provided. After the basic SHIVA laser system has been successfully operated on target, anticipated to occur in late 1977, the irradiation capabilities of the facility will be augmented with the addition of nonlinear optical components and pulse shaping elements. The nonlinear wavelength converters will permit delivery of 2 kilojoules of energy (or more) at the second and fourth harmonics of the fundamental wavelength.

Based on the implosion simulation calculations described above, it is believed that the operating performance characteristics of the SHIVA laser will be adequate to achieve the first, and possibly the second, major milestones of ERDA's Laser Fusion Program: (1) "Significant TR-burn" defined as a TR yield of approximately ten per cent; and (2) light breakeven.

Large lasers for fusion experiments must not only generate terawatts of peak power in subnanosecond pulses, but the output radiation must be focusable onto small (100-300 μ) fusion targets. Focusability of terawatt level lasers requires stringent control of the phase and amplitude of the output beam. At the outset of the SALVA project it was recognized that commercially available neodymium glass (Nd:glass) lasers, utilizing large diameter glass disk amplifiers, could not be scaled into the terawatt, subnanosecond regime with acceptable focusing properties. A program activity was therefore established to create, develop, and test the physics and technology for large-aperture disk amplifiers and associated components in support of the SALVA project.

The design of fully integrated fusion lasers is dominated by the non-linear interaction of the laser radiation with the dielectric glass medium. This phenomenon is illustrated in Figure 3, in which a low intensity ($< 3 \text{ GW/cm}^2$) laser beam passes through the Nd:glass amplifying medium without (appreciable) amplitude or phase distortion. An intense beam ($> 5 \text{ GW/cm}^2$), however, will tend to break up upon passage through the glass as a result of the non-linear response of the dielectric medium to the optical electric field. Unavoidable small-scale variations of amplitude or phase on input beam wavefront will be rapidly amplified relative to the average beam amplitude, causing degradation of the beam. The effect will accumulate as the beam passes through each optical element, ultimately causing physical damage to the laser optical elements, and a loss of focusability onto small fusion targets. To minimize these deleterious intensity dependent processes, one must design large-aperture glass-disk amplifiers with high specific gain coefficients, consistent with the limits of superfluorescent and parasitic-mode loss mechanisms of laser amplifier media. During the

past three years, we have developed a full methodology for the design of optimized Nd:glass lasers for scaled fusion experiments, based on extensive laser component and systems computer modeling and verified through the successful development and test of the world's largest aperture, high-gain disk laser amplifiers and laser amplifier chains. A comprehensive review of this program activity will appear in the LL Laser Fusion Annual Report, to be released on May 1, 1976. Figure 4 is a photograph of the "Cyclops" Nd:glass amplifier which will be used as the primary engineering test bed for the development of laser hardware and engineering techniques. The cyclops chain consists of a 1000 cm long locked resonator delivering a well-controlled, diffraction-limited, typically 150 psec duration, 100 J pulse which is amplified in spatial profile by a "soft" aperture, and then amplified in glass rod amplifiers up to the joule level. From this point, the beam is passed through a series of disk amplifiers, polarizers and Faraday rotators of increasing aperture. The latter optical elements prevent damage of the laser chain due to target back reflections and prevent parasitic oscillation from occurring along the chain. This chain has been operated with a peak-power output in excess of a terawatt utilizing a final disk aperture of 20 centimeters. Figure 5 is a photograph of the world's largest disk amplifier containing two 30 x 60 centimeter disks pumped to a relatively large stored energy density of 5.4 J/cm². This amplifier module was developed to establish the limits of Nd:glass disk amplifier performance and to provide the maximum in design output for the SLL laser. Detailed laser system analysis indicates that the use of disk amplifiers of such large aperture are sub-optimal from a cost/performance point of view.

A scale model of the SHIVA laser system is shown in figure 6. The physical scale of the laser is indicated by the number in figure adjacent to

the laser. As shown, the laser will utilize 20 parallel chains driven by a common master oscillator. Each chain will deliver a terawatt of peak power to the target, placed in the chamber shown in the foreground. The laser, its space-frame and the target chamber will be arrayed in the HELF facility as shown in Figure 7. The construction of the HELF facility has been underway since Fall 1974 and will be available for beneficial occupancy in the spring of 1977. The conceptual and preliminary engineering design of the fully integrated HELF laser has been successfully completed, predicated on laser performance. Detailed engineering design is in progress and will lead to construction in progress. In addition, its support of the HELF laser project, the development of prototype laser hardware and systems has provided and represents the technology to construct near-future laser irradiation facilities for implosion and plasma jet experiments.

The first of these irradiation systems, JAWBS I, has been operational since late 1974 and was used to compress the DT targets discussed below. This system is shown in Figure 8. The foreground shows the master oscillator, beam-shaping optics and preamplifiers. A series of four disk amplifiers which amplify the beam up to about 0.1 terawatt can be seen in the left center portion of the photograph. At this point the beam is diverted to the left, passed through an additional nine centimeter disk amplifier, and directed into the target chamber seen in the background. In this one-beam configuration (JAWBS I), the laser delivers 0.2 terawatts of focurable power to the target. The system has been operated with typical Gaussian pulse widths of 100 psec. At present the laser is being converted to a two-beam configuration (JAWBS II) by splitting the 0.1 terawatt beam into two beams which are each reamplified back to 0.2 terawatts (for a total focused peak power of 0.4 terawatts) and impinged on the

to the target chamber colinearly in opposite directions.

A second, more powerful irradiation system called A-10S has been designed and is now in construction. It will first be operated in a two-beam configuration (A-10S II) providing a total peak power of two terawatts using two disk amplifiers of nominally 20 centimeter diameter. This system is expected to become operational in December 1982. The system is designed to permit the addition of two additional beams (A-10S III), providing a total maximum peak power of four terawatts. The sequential operation of these systems will provide a continuously increasing target fluence over the next 6 years until 124 J/cm² is reached. This program will be used to establish increasing confinement conditions, to study the effects of our understanding of the fundamental laser-plasma coupling, and fusion processes.

DIAGNOSTICS

The development and application of detailed, high resolution, diagnostics techniques and instrumentation for laser and laser-plasma interaction studies is fundamental for rapid development of laser fusion and is therefore an essential element of our program. The development of high peak power lasers generating pulses on a picosecond time scale requires us to be able to measure the detailed properties of such pulses as well as the effects of their interaction with matter. Laser target is initially 10 μ m to 100 μ m in size and eventually be compressed to densities 10,000 times liquid density and temperatures of tens of billions. The requirements for the necessary measurements can be summarized by noting that the ranges of interest are 1 psec to 1 nsec in time, 10^{16} cm⁻³ to 10^{26} cm⁻³ in density, 50 eV to 500 keV in temperature and 1 μ m to 100 μ m in space. Our goal is to be able to make such measurements with temporal and spatial resolutions of 1 nsec and

1. In order to have a wide extension from the infrared to x-ray regions of target plasmas yield vital information on the physical processes occurring and their characteristics must also be measured in detail.

An important consideration in our diagnostics selection and development work is a requirement for as much data acquisition as possible on each laser shot. For this reason we would, if at all possible, "sample" techniques which require acquisition of data on many shots in order to obtain a set of data. Together with the implementation of such suitable techniques, the on-line experimental procedure is often a requirement for computer control and for the development of suitable data acquisition and analysis systems. The development of this capability together with the hardware interface and software, is a recent, and growing, important feature of our diagnostic activity.

Diagnostics development is accomplished both programmatically on-line, in the laser-target experimental areas, and off-line for research and for more lengthy and complex developments. Today, I would like to describe just two recent developments in the area of x-ray diagnostics: a focussing x-ray microscope and an x-ray streak camera."

Two simple x-ray microscopes, based on the work of McGee,⁵ have been constructed to operate in the energy range 0.2-8 keV, offering improved spatial resolution over conventional x-ray pinholes, particularly at low x-ray energies. The microscope is based on the fact that near grazing incidence, x-rays reflect almost totally from smooth surfaces. For a given material, soft x-rays are efficiently reflected while rays of increasing energy reflect with decreasing efficiency, up to cut off energy above which the reflection is zero. For low-Z materials, the energy cut-off is quite sharp. The single lens microscope constructed for use in laser

fusion experiments is shown schematically in Figure 9. It consists of two glass mirrors, each ground and polished with a slightly concave cylindrical surface. The mirrors are oriented so that a small fraction of x-rays from the source are reflected from both surfaces, and in such a way that the two line foci form a point-to-point image of the source.

Experiments viewing laser produced plasmas through fine mesh indicate that spatial resolution of five microns has been achieved over a field of view of several hundred microns. Studies also indicate that a somewhat more complex lens will be able to achieve a resolution less than a micron. Based on the performance of the single lens, a four lens microscope was also built. This device is capable of taking four pictures at the same time, each in a different spectral range.

Several years ago, we developed a ten-picosecond-resolution, optical streak camera as a diagnostic for subnanosecond laser pulses. We have recently modified this camera by replacing the optically sensitive photocathode with an x-ray photocathode, sensitive in the one to ten kilovolt energy range. This photocathode was formed by depositing a 100 Å layer of gold on the rear surface of an 8 micron thick Be vacuum window. The performance of the x-ray streak tube was explored by streaking the x-rays from two plasmas created by 150 psec long laser pulses separated by 500 psec. These experiments indicate a time resolution for the camera of better than 50 psec and probably 30 psec. The coupling of the x-ray streak camera with appropriate spectroscopic instruments will permit time resolved x-ray spectra to be taken of imploding targets. We intend also to mate the x-ray streak camera to improved x-ray focussing microscopes in order to observe the time evolution of an imploding target in its own x-ray emission. Such capabilities will be profoundly useful in the type of target irradiation experiments to be described next.

FUSION EXPERIMENTS

An important milestone along the path to laser fusion power was achieved in 1974, the demonstration of several successful laser-driven implosions. In these experiments, hundred-fold volume compressions and fusion neutrons were produced. In the first successful laser implosion experiments, which were carried out by KMSF in May 1974, about 10,000 neutrons were measured. Since then neutron production has been increased into the 10^6 to 10^7 range at KMSF. About 10,000 neutrons were also produced in the first implosion experiments at LLL in December 1974 and increased up to 10^6 in subsequent experiments. KMSF used fusion micro-capsules consisting of hollow glass shells, typically 50 microns in diameter with one micron wall thickness, filled with low density D1 gas (10^{-3} - 10^{-2} g/cc). Although similar micro-capsules were fabricated at LLL beginning in 1970, more complex targets have been used in the LLL experiments.

In a KMSF experiment, the fusion capsules were symmetrically irradiated with approximately 60 joules of laser energy via a complex focussing system consisting of two laser beams, f/0.6 lenses, and elliptic mirrors. The incident laser pulse, 300 psec, full width-half maximum, was optimally shaped via a pulse stacker. About 10 joules, or 10-20 per cent of the incident energy was absorbed by the target. In the experiments at LLL, the capsules were irradiated asymmetrically with a single laser beam delivering 15-20 joules in a Gaussian pulse 100 psec in width. The laser beam was focussed by an f/1.0 lens and about 10 joules, or 50% of the incident energy was absorbed by the target.

Table i summarizes a comparison of experimental neutron yields with LASNEX-calculated neutron yields for seven implosion experiments performed at LLL and for two implosion experiments performed at KMSF. Calculations of neutron yields are in agreement to within a factor of three for neutron

yields varying by a factor of a hundred. In addition, the LASNEX calculations agree out to 10 keV with the measured thermal component of the x-ray spectra measured at LLL. The high energy x-ray measurements indicate that the suprathermal electron spectrum is somewhat softer than previously assumed.

It should be stressed, however, that not enough neutrons have been generated in any single experiment to allow experimental confirmation of their true thermonuclear origin, that is, corresponding to the calculated one keV ion temperature of the imploded DT fuel. However, the agreement of the neutron yields with the LASNEX predictions is supportive evidence of their thermonuclear/implosive origin.

As an example of the target irradiation experiments performed at LLL, refer to Figure 10. This photograph shows the so-called "ball-and-disk" target, based on a Los Alamos target concept, as modified and constructed at LLL (this target is the first entry in Table I). It consists of a glass disk mounted on a stalk. Attached to the glass disk is a glass shell filled with DT gas at low density. A sketch of the single-sided irradiation geometry is shown on the right of Figure 10. This target is of the exploding pusher (isothermal) type and was irradiated at 0.2 terawatts (100 psec). A neutron yield of 7000 was obtained, in rough agreement with that expected. Figure 11 illustrates the kind of x-ray imagery which can be obtained using the x-ray microscope described above. This photograph is a black and white rendering of a computer-enhanced (color coding) micrograph taken with the x-ray microscopes. In this time integrated picture, the hot (x-ray emitting) exploding shell and disk can clearly be seen. The inward moving pusher compressed the DT to nearly the original pusher density (~ 1 g/cc) and heats the central (core) region to temperatures of about one keV. The diameter of the target shell was 60 microns, giving some measure of the resolution of the microscope.

Using various x-ray sensors in combination, the absolute shape and intensity of a target x-ray spectrum from 0.2 keV to 80 keV can be recorded in a single shot. Figure 12 shows such a spectrum obtained for the first successful implosion experiment which yielded 1.2×10^4 neutrons. This type of information is critical for complete understanding of the implosion dynamics.

FUTURE PROGNOSIS

The physics of the laser fusion process is extremely complex so that any prognostication of the growth of neutron yields is at best speculative. Our best guess in this area is, of course, predicated on the ability of LASNEX and other codes to properly treat the important physical processes. We have in fact based our program activities in target design, target fabrication, laser development, diagnostics development, and irradiation systems on the insight provided by these large simulation codes. We were, therefore, highly gratified that the early experimental data on fusion implosions were reasonably predicted by LASNEX. Furthermore, some problems which could make high-density, isentropic implosions very difficult appear to be less severe than anticipated earlier; laser energy is being efficiently absorbed, at least in the LLL experiments and the suprathermal electron tail is relatively soft. To the extent that these early indications continue to be sustained we can venture some estimate of the rate of growth of neutron yield. This rate will be determined by the speed with which high energy, high irradiance lasers can be brought on line. Figure 13 plots an estimate of neutron yield (roughly corresponding laser peak-power) as a function of calendar year. The regions of operation of existing and planned Nd:glass lasers discussed above are shown together with experimental

neutron yields to date. In the context of the total national fusion program, including both magnetic-confinement and inertial confinement fusion, this projection can be illustrated by Figure 14. Here we plot the plasma ion temperature versus the Lawson number (density-confinement time product in sec/cc). The shaded region represents an energy breakeven condition.

The black circles represent achieved performance of various magnetic confinement machines and the open circles represent the projected performance of CTR machines just coming on line or presently planned. The best performance of a laser driven implosion (Lawson number of 2×10^{12} and ion temperature of one keV) is shown for comparison (also in black). The estimated trajectory for laser driven implosions is indicated by the crossed circles. Now that the technical foundations have been developed to construct lasers of the sizes indicated, it is apparent that we are entering a period of rapid learning, and substantial progress is anticipated in the next few years.

Due to time constraints, several additional significant program activities can only be mentioned. First, we have been conducting a small but productive effort in the development of laser fusion reactor concepts. These studies have examined both fission-fusion hybrid and pure fusion reactors. On the basis of these studies one can begin to define scenarios for the development of laser fusion power once scientific feasibility has been demonstrated. Additionally, the operating characteristics of lasers required for reactor applications can be scoped. In the interest of minimizing the time between a successful scientific feasibility experiment and the development of power reactors, we have developed an aggressive program activity for the discovery and technological development of new high peak- and average power, visible gas lasers. Armed with the laser performance requirements for reactors, we have been able to direct our search for candidate atomic and/or molecular laser media into fairly narrow areas.

This approach has yielded several early successes with the demonstration of three new visible lasers, all based on the green "auroral" emission of the excited oxygen atom. Using high-current density relativistic electron beam pump sources, we have produced coherent oscillation in the rare-gas oxygen excimers XeO, KrO, and ArO. Early experiments on these laser media suggest that these systems (or variant forms of them) may be scalable to the range of interest. A firm evaluation of these systems is expected during the next year, and several alternative laser medium types will be vigorously pursued in parallel. By virtue of this relatively small but growing activity, it is hoped that lasers for fusion applications will not only be known, but in a relatively advanced state of technological development when needed.

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FIGURE CAPTIONS

1. Micro-capsule fusion target, consisting of a stalk and spherical glass shell filled with low density DT gas. The structural cross-section is shown at the left. Photograph at right shows target constructed at LLL.
2. Calculated TH yields for exploding pusher and isentropic laser driven implosions.
3. Nonlinear optical beam degradation. Low intensity beam shown on top, passes through dielectric medium without distortion of its spatial profile. A high intensity beam breaks up spatially upon passing through dielectric medium due to the nonlinear response of the medium.
4. Photograph of the Cyclops neodymium glass laser system at LLL. Operating at over one terawatt peak power, this laser utilizes large aperture (~ 20 cm diameter) disk amplifiers to minimize nonlinear beam distortion.
5. Largest of the Nd:glass disk amplifiers developed in support of the SHIVA project. Each of the two elliptical disks measures nominally 30×60 cm along the principal axes. Pumped with xenon flashlamps this disk amplifier stores up to 0.4 joules/cc.
6. Scale model of the SHIVA laser planned at LLL. This twenty beam Nd:glass laser will deliver 20 terawatts of peak power to a target placed in the irradiation chamber.
7. Sketch of the SHIVA laser and target chamber installed in the High Energy Laser Facility (HELF).
8. Photograph of the JACUS Nd:Glass laser irradiation system. Configured as a single beam device, the laser delivers 0.2 terawatts of peak power to fusion targets.
9. Schematic of single-lens, focussing x-ray microscope.

10. Ball-and-disk target. Photo at left shows ball-and-disk target constructed at LLL. Sketch at right shows geometry of laser irradiation.
11. X-ray microscope picture of imploded ball-and-disk target. This photograph is a black and white rendering of a computer-enhanced (color coded) x-ray microscope exposure. Gray (color) scale provides calibration for intensity data.
12. Measured x-ray spectrum from 0.2 to 80 keV taken on a single target irradiation producing 10^4 neutrons. Correct relative intensities across the entire spectral range are provided.
13. Expected neutron yields calculated for various solid state irradiation systems existing or planned at Livermore, shown as a function of the year when each system is expected to be operational. Approximate corresponding peak-power rating is indicated on the right hand scale.
14. Ion temperature - Lawson number plot for various magnetic-confinement and inertial-confinement experiments. Black circles indicate achieved performance levels (density-confinement time product in sec/cm^2). Open circles indicate projected performance of planned magnetic confinement experiments (machines). Crossed circles indicate projected performance of planned inertial confinement experiments (machines) at the Lawrence Livermore Laboratory.

COMPARISON OF LASER FUSION EXPERIMENTS AND CALCULATIONS

Target	Experimenter	Laser energy joules	Pulse duration picoseconds	Experimental neutron yield	Calculated (LASNEX-LLL) neutron yield
Ball & Disc (LASL concept)	LLL	~20	~100	7,000	
LLL Design A	LLL	~20	~100	30,000	50,000
LLL Design B	LLL	~20	~100	30,000	100,000
LLL Design C	LLL	~20	~100	100,000	200,000
LLL Design D	LLL	~20	~ 70	300,000	500,000
LLL Design E	LLL	~20	~100	400,000	800,000
LLL Design F	LLL	~23	~100	1,000,000	3,000,000
KMSF sphere	KMSF	~60	~300	400,000	600,000
KMSF sphere	KMSF	~60	~300	7,000,000	20,000,000

TABLE I

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

X-RAY MICROSCOPE

Fig. 9

Fig. 10

Fig. 11

Fig. 12

Fig. 13

"BREAK-EVEN" PLASMA CONDITIONS FOR FUSION POWER

Fig. 14