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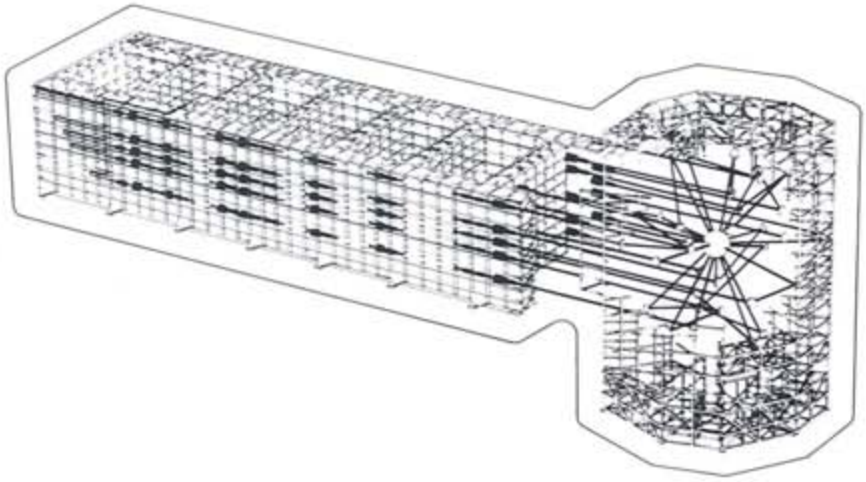

NATIONAL SECURITY

The Solid-State Laser Program

The basic objective of the solid-state laser program at LLL is to provide the high-power pulsed lasers needed to study laser fusion target implosion. We estimate that we will need laser pulses with peak power greater than 200 TW to perform a scientific feasibility laser fusion experiment. This corresponds to a 200-kJ pulse delivered in 1 ns. We have developed a laser technology, based on glass doped with neodymium ions, to accomplish this goal. We have demonstrated 4.6-TW operation with the Argus laser system, and we will soon demonstrate over-20-TW operation with the Shiva laser. We are designing the Nova laser for 200- to 300-TW operation by 1984.

To demonstrate the basic ideas of laser fusion, solid-state glass lasers have been intensively developed at LLL. These ideas, discovered here in the early 1960's, rely on very-high-power lasers to implode D–T targets. Extensive computer modeling with the LASNEX code determines the laser energy, power, and pulse shape for each target design. In 1973–1974 the results of target studies, together with estimates on laser technology development rates and funding rates, were assembled into the plan shown in Fig. 2 on p. 3.

We need laser performance at levels of over 100 TW and 100 kJ for breakeven target yields and levels of 200 to 300 TW to prove the scientific feasibility of laser fusion. In 1972, when the laser work described in this article began, the peak power of short-pulse solid-state lasers was limited to about 0.1 TW. We are now producing 4.6-TW pulses with the Argus system, and we will soon be operating Shiva at 20 to 30 TW.

Figure 1 is a brief pictorial record of our laser systems, from Janus I, the first single-beam target system, to multiarmed Shiva, now being assembled and tested for operation in the 10- to 30-TW range. The Shiva Nova laser, discussed later, is being designed to provide the laser power for the scientific-breakeven and high-gain scientific-feasibility goals.

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Fig. 1. A brief history of laser developments at LLL. Starting in 1974, the Janus laser (*top*) operated at 0.2 TW per beam and drove LLL's first neutron-yielding laser fusion reactions. This versatile, relatively simple system is now dedicated to detailed fusion physics and equation-of-state experiments.

Cyclops (*center*) produced 0.6 to 1.0 TW with one, singly spatial-filtered, 20-cm-aperture beam. Although briefly used for laser fusion experiments, Cyclops' real contribution has been as a prototype, large-aperture laser chain. Most innovations in system design, laser components, automatic alignment, and control, now used on Argus and Shiva, were first tested on Cyclops.

Argus (*bottom*) is currently the world's most powerful laser. It has produced 4.6 TW with two beams and is the workhorse of the laser fusion program. In a recent experiment it produced a record laser fusion yield—10^9 neutrons.

Shiva (*opposite page*), now under construction, employs automatic alignment and system control by computer. One beam is now completed through to the 15-cm aperture and has produced 526 J in 1 ns. This laser will produce more than 10 kJ in 1 ns with 20 such beams later this year (see the brief on p. ii) and will begin laser fusion experiments early in 1978.

We chose neodymium–glass lasers for development into the present fusion laser systems at LLL for several reasons:

- Calculations showed that the neodymium–glass laser wavelength (1.06 μm) was short enough to couple efficiently to laser fusion targets.
- Laser glasses doped with neodymium ions were developed and were scalable to large sizes.
- Commercially available optical glass could be used for lenses, windows, and other glass parts.
- Diagnostic instruments such as photodiodes, photographic film, and streak cameras operated satisfactorily with 1.06-μm radiation.

To meet our goals we began investigations on the most crucial aspects of the solid-state laser design: propagation limits, component design, and system integration and operation. This article outlines the progress we have made and the impact of innovation on future designs.

PROPAGATION

Every energy-transmitting system has its power-handling limit; in lasers, one limit is reached at intensities of 20 to 30 GW/cm^2, when the electric field of the laser light is strong enough to distort the electron cloud surrounding the atoms in the laser glass, lenses, and windows. This distortion in the electron cloud causes a local increase in the index of refraction of the glass. The increase is proportional to the intensity, I, of the light beam (in W/cm^2) multiplied by the nonlinear refractive index n_2. This increase in refractive index focuses brighter portions of the beam, intensifying them and still further increasing the index of refraction.

These intensity fluctuations grow exponentially as the beam travels through the glass. Ultimately, this self-focusing instability can break up the beam into thousands of tiny filaments that cannot be focused onto the target and that may damage the glass. As long as the ripples are small, the intensity of a ripple may be calculated with relatively simple formulas. For example,

$$I_{\text{ripple}} \cong I_{\substack{\text{initial}\\ \text{ripple}}}\, e^{2B}$$

expresses the exponential growth of the ripple intensity, and

$$B \propto \int_0^L n_2\, I_{\text{beam}}\, d\ell$$

describes how the beam length in the material L, the nonlinear index of refraction of the material n_2, and the average beam intensity I_{beam} all influence the rate of exponential growth B.

Although we take great care to have the highest quality optical components and keep them extremely clean, it is practically impossible to produce beams with less than 1% initial ripple. This means that B must be held to less than about 2.5 if the ripples are not to exceed the beam intensity itself, breaking the beam into filaments. This B limit is a major design constraint.

The simple relationships outlined above also provide the strategy for maximizing the performance of our laser systems. Minimizing the path length L (in the material) with high-gain laser glass and thin optical elements directly reduces the value of B. We choose or develop optical materials with low nonlinear refractive indices (low n_2). As the beam is amplified, its diameter is increased to reduce beam intensity. Finally, the laser beam is periodically filtered to remove the worst of the ripples. Each filter effectively resets B to zero and restores the initial ripple intensity to a low value (Fig. 2). Thus the strict B limit applies only to the components between spatial filters. This strategy, with five sequential filters, enables the Argus system to produce pulses of more than 2.5 TW from a single 20-cm-diam beam—five times our initial Cyclops results (without spatial filtering) and nearly ten times any other single-beam system operating in the world.

The development of a detailed physical understanding of these propagation processes, the development of a strategy for effective control of the self-focusing instability, and the development of new low n_2 materials stand as major accomplishments of the LLL laser program and are keys to the

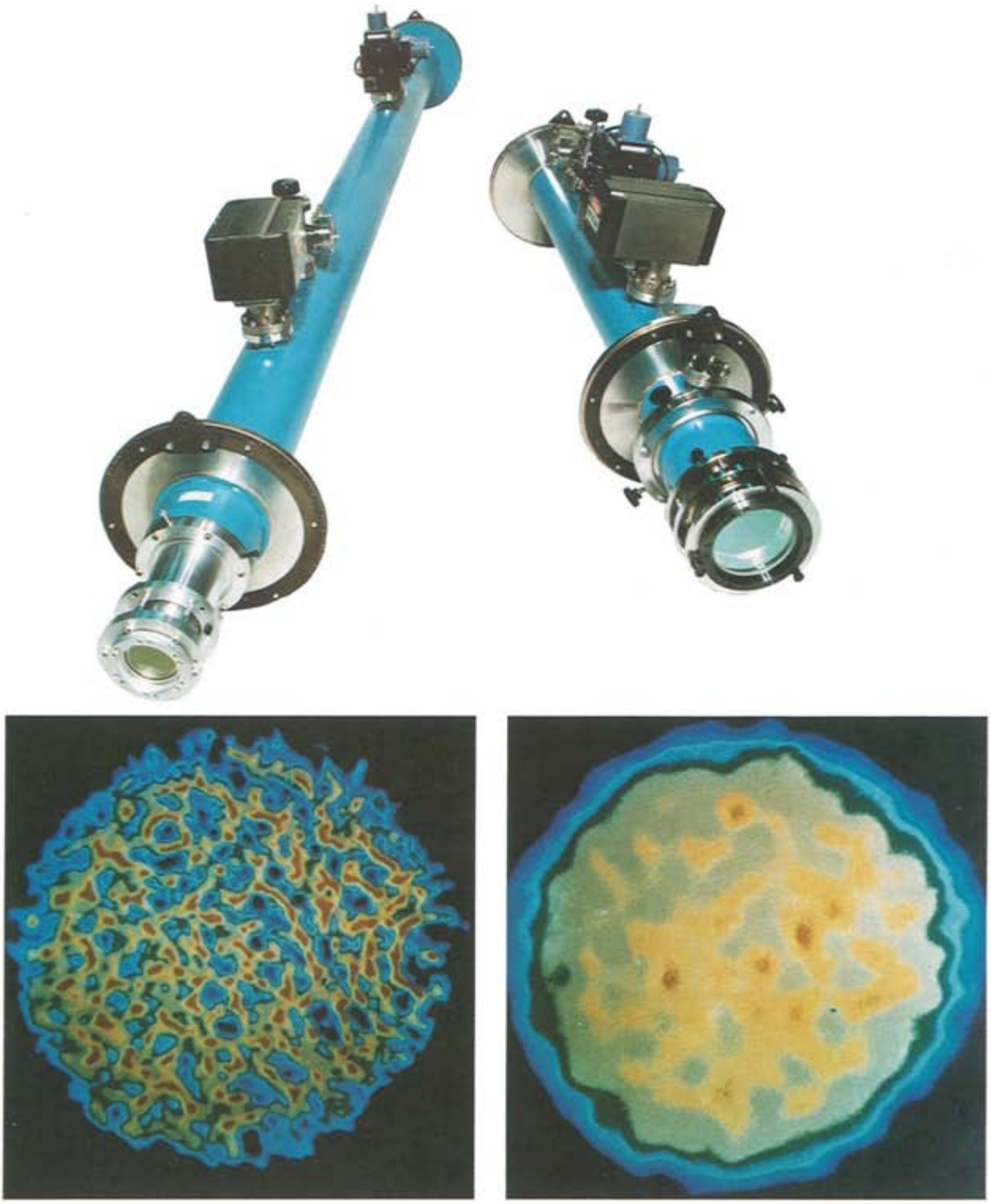

Fig. 2. Spatial filters are incorporated into our high-power laser systems to prevent the buildup of high-intensity ripples in the beam profile. Spatial filters of the type being used on Shiva are shown in the top portion of this figure. The beam is filtered by focusing it through a pinhole inside an evacuated tube and allowing it to expand until it is recollimated by a second lens. Diffraction causes the spatially small intensity ripples to focus to a large spot, while the smooth portion of the whole beam focuses to a small spot that passes through the pinhole. Only a very small fraction of the beam energy is removed in cleaning up the intensity profile. Beam quality on Cyclops before and after spatial filtering is shown in the bottom portion of the figure. This technique, first demonstrated on Cyclops, is applied at five points in the Argus chain and four in the Shiva chain.

operation of any high-power short-wavelength laser system.

Another limit to the flow of energy through optical materials is catastrophic breakdown. At high laser intensity the electric field of the light accelerates a random free electron to a velocity at which it knocks other electrons free and initiates electron-avalanche breakdown. This process multiplies the number of free electrons that in turn are accelerated by the laser beam. With the development of the local plasma more laser energy is absorbed in the material, and damage occurs. At first LLL laser designs were limited by self-focusing, not by material breakdown. With improved control over self-focusing and longer laser pulses (to implode larger targets more isentropically), laser damage to optical components, especially to thin-film coatings, has become an important design constraint.

COMPONENTS

Components to provide the required functions of a laser system have been designed with system constraints in mind. The most important from a performance/cost viewpoint are the laser disk amplifiers. These devices, pictured in Fig. 3, uniformly amplify a laser pulse from 0.01 TW to over 2.5 TW in current laser chains. Since they represent more than half the cost of a laser chain, it was important to develop a predictive performance/cost model.

In a disk amplifier the glass disks are excited by long xenon-filled flashlamps. Each flashlamp dissipates about 10 kJ of stored electrical energy in 600 μs, with 80% of this energy radiated as visible and near-ultraviolet light. About 5 to 10% of the flashlamp light is absorbed by the neodymium ions in the glass, and about 15% of this absorbed light is available as extractable laser energy.

We have developed extensive numerical simulation tools to describe the flow of energy from the capacitor storage system to the optical gain in the laser disks. As a consequence, we can optimize the thickness of laser glass, the stored electrical energy, the number of neodymium atoms in the glass, or other properties—depending on our goal. For example, a 20-cm-diam disk amplifier optimized for short-pulse laser performance contains three laser disks, each 3.2-cm thick and doped with 1.7×10^{20} neodymium ions/cm^3. This amplifier costs about \$100 000. The cost of the mechanical structure and other fixed-cost items is \$21 000, the laser glass costs \$25 000, and the energy storage is \$61 000. The optimum design for this amplifier is a careful balance between the cost of the hardware and the cost associated with the reduction in performance due to self-focusing. For example, the hardware cost is reduced by using fewer capacitors and lower flashlamp pumping of the disks, but the B-limit cost "penalty" is increased by the resulting low gain in the laser disks. This occurs because, for a fixed B, the beam intensity must be reduced if the beam path length in the laser material is increased.

Many other components besides disk amplifiers combine to make a stable laser fusion system. They include a high-energy capacitor bank, a laser master oscillator, small glass rod amplifiers, the spatial filters described previously, and one-way isolators to stop reflections.

Fig. 3. Disk amplifiers, the basic working component of our laser chains, have been thoroughly engineered at LLL. This Shiva 20-cm disk amplifier has a gain of 2.5, stores 1.8 kJ of laser energy, and can produce 2 TW.

The 20-kV, 22-MJ Shiva capacitor bank drives the laser flashlamps with a 600-μs current pulse. Production assembly techniques developed at LLL with industrial assistance have reduced the energy-storage cost of the banks to about 0.25 \$/J. Extensive computer control and system diagnosis make this a highly reliable system.

The laser master oscillator, which generates the initial pulse, operates at the 1-MW level. It is exceptionally stable, with amplitude, phase, and pulsewidth fluctuations of less than $\pm 2\%$. The pulse shape is originally Gaussian but we can tailor it to any desired shape by diverting part of the beam, splitting it into as many separate beams as necessary, amplifying them separately, and adding them to the main beam coherently. Figure 4 shows the actual shaped pulse from an Argus target experiment.

The small glass rod amplifiers boost the initial pulse from the megawatt level to the 0.01 TW needed for injection into the disk amplifier system.

Our system includes two kinds of isolators to provide a one-way direction for the laser chain: Pockels cells and Faraday rotators. Pockels cells also serve as high-speed shutters, but so far the largest Pockels cell is about 5 cm in diameter. Faraday rotators are large-aperture devices that pass light only in the forward direction. These isolation devices safeguard the laser from target reflection, which may be as much as 50% of the incident beam, and from any optical feedback within the system.

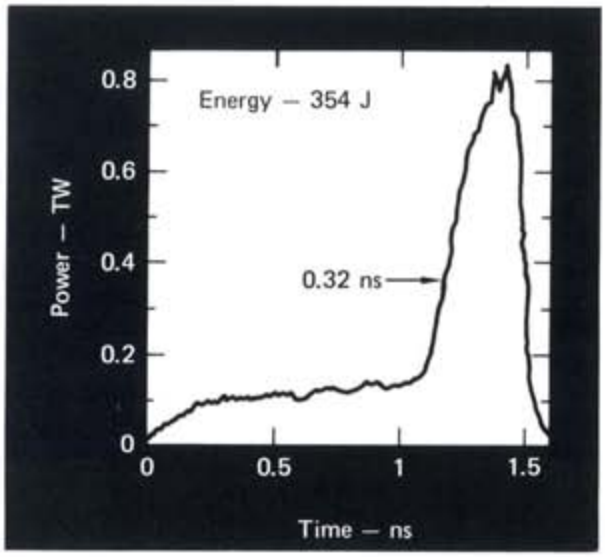

Fig. 4. Pulse temporally shaped by Argus laser. Unmodified pulses as they come from the laser master oscillator are Gaussian, not necessarily the best shape for driving the target implosion. To reach the highest compression and temperature efficiently, we need specially shaped pulses. The pulse shown was constructed by stacking a coherent sequence of pulses of appropriate intensity, all generated from a single initial pulse, a Gaussian 0.32 ns wide.

SYSTEM DESIGN

Using our models for amplifier performance, for propagation and spatial filtering, and for isolation, we can mock up the various components into a system and model overall performance and costs. Computer simulation permits us to examine thousands of laser configurations and find the best buy, subject to such constraints as pulse duration, target reflectivity, and fixed costs for chain diagnostics and alignment. The most cost-effective system is the one that delivers the required power and energy to a laser fusion target for a minimum cost.

By now we have extensive experience in estimating the costs associated with laser glass, capacitors, diagnostics, controls, alignment, the spaceframe, and other items required to make a system operate. We find that the cost of a laser system breaks down into three roughly equal segments: the optical components, the electrical components, and the mechanical subsystems. This partitioning of costs tends to dilute the effect of cost-reduction efforts: a 30% cost reduction in any one segment would reduce the overall cost only 10%. However, a technology advance that increases the system power by 30% produces a full 30% increase in cost effectiveness. Hence we tend to emphasize technology that increases power output, although cost reduction is important too. Our cost effectiveness has been steadily increasing, from about 0.2 TW/million dollars on Cyclops to an estimated 2 TW/million dollars on Shiva Nova.

PROGRESSION OF SYSTEMS

The LLL series of laser systems is planned to satisfy a variety of goals. The Cyclops laser was designed as a laser test bed to acquire data needed

for system performance modeling. The Janus system, built of components developed for Cyclops, was used to obtain our first laser fusion target results.

Our experience in shooting targets on Janus pointed up the need for system reliability. Laser misfires represent a large waste of resources. Also, the Shiva and Shiva Nova systems will be very large with many complex subsystems. These combined pressures forced us to intensify work on automatic optical alignment and digital control systems.

The Argus laser system was designed for high-compression target experiments. It was also the first opportunity to install multiple spatial filters, amplifiers designed for clean operation, new apodization techniques, and complete optical diagnostics. The resulting system, initially conceived to provide 3-TW pulses, currently operates at 4.6 TW on target. A target experiment last fall produced 10^9 neutrons. The performance of this system substantiated the Shiva design approach.

The Shiva system, shown in Fig. 5, is the culmination of our effort to build a laser capable of driving significant thermonuclear burn—1% of scientific breakeven. This laser system, optimized for high power, incorporates the most recent LLL-developed technology: multiple spatial filters, image relays, large-aperture Pockels cells, and damage-resistant optical coatings. It employs, for the first time, automatic alignment and automatic preshot and postshot system diagnoses to ensure reliability. Eventually the entire setup will be computer-controlled, with largely automatic data processing.

This system is presently in final assembly and checkout. One beam has already been fired and has met its design goal of 0.5 kJ in 1 ns; for 20 beams this would amount to 10 kJ in 1 ns or 10 TW of power (see brief on p. ii). When fully assembled and operated at 0.1 ns, Shiva should provide more than 20 TW of laser power.

Encouraged by the continuing advances in glass research and the successful performance of these systems, we have begun to design Nova (Fig. 6), a neodymium-glass laser to attain laser fusion breakeven and to demonstrate scientific feasibility. Experience gained so far suggests that such a solid-state glass laser can be constructed, with low technological risk, several years ahead of other potential short-wavelength laser systems and within the projected cost of $195 million.

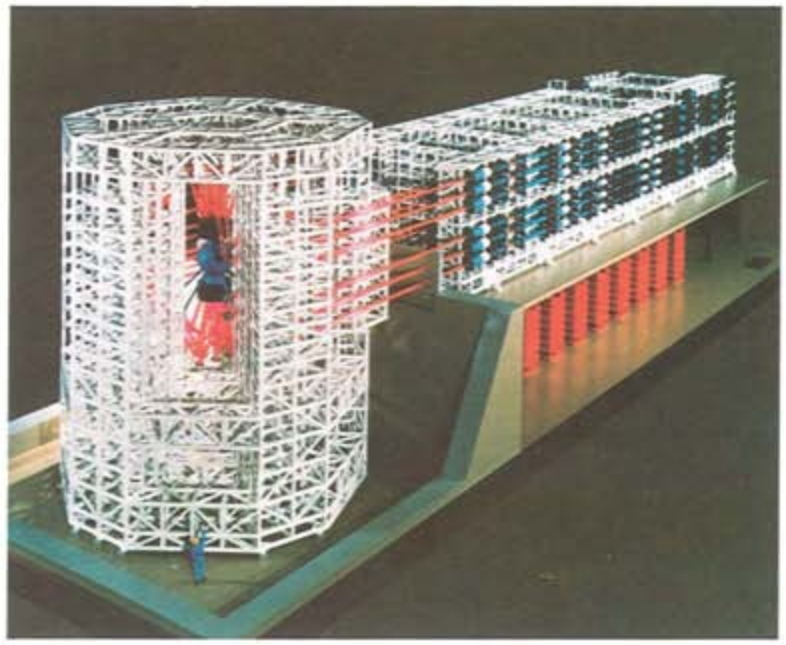

Fig. 5. A model of Shiva used during design to verify and improve the system layout. The 20 laser chains are mounted on the laser spaceframe, 10 on each side. All 20 beams converge onto the target chamber mounted in the target spaceframe.

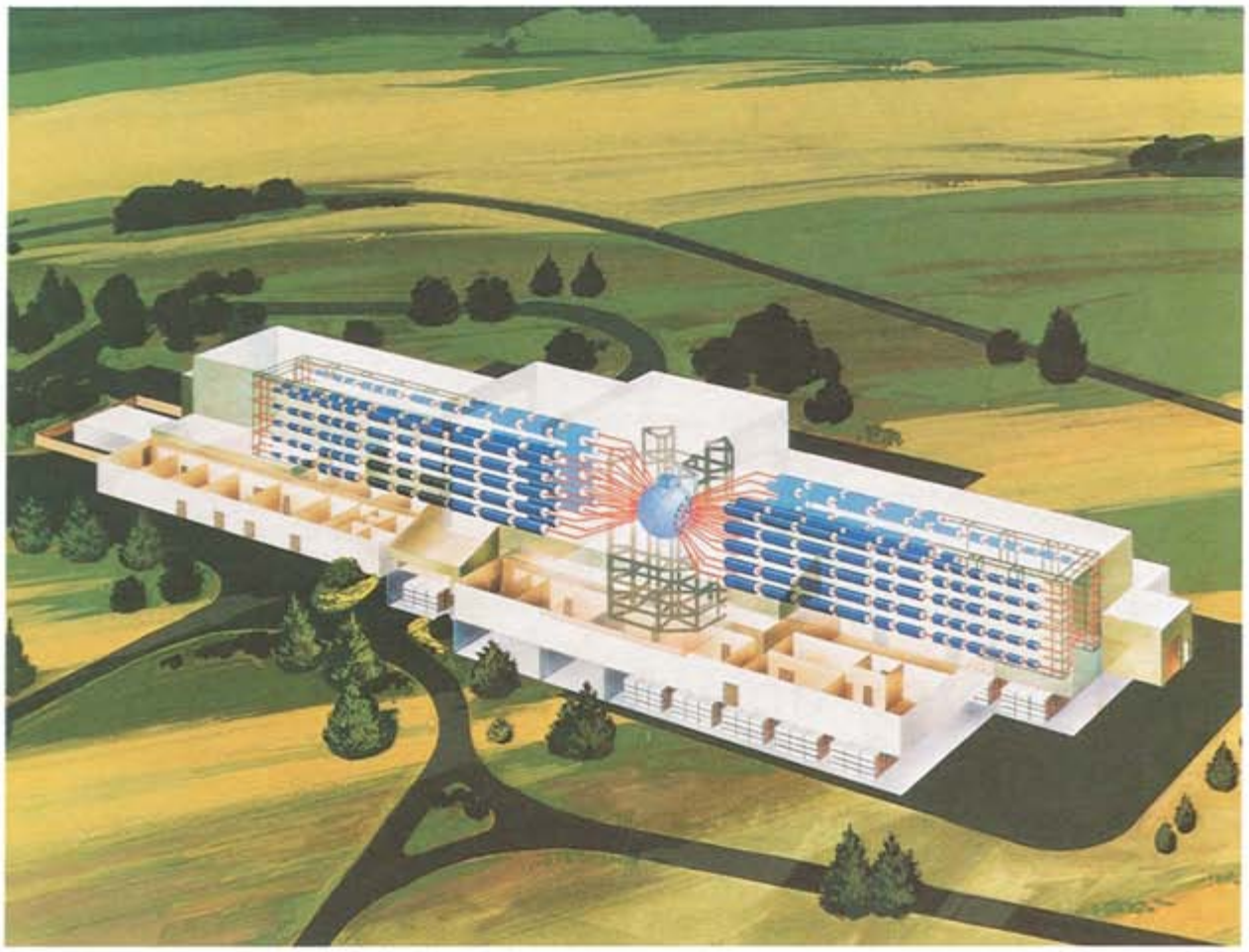

Fig. 6. Nova is a planned 200- to 300-TW laser system based upon Shiva technology but with improved laser materials. This system will operate at about 100 TW at first, using only the east (*right*) laser bay. The Shiva facility in the west (*left*) bay will then be converted to the Nova configuration to complete the system construction in 1983 at a cost of $195 million.

The technological advances that make Nova possible are many, but among the most important are the development of new laser glasses with low values of n_2; the success of multiple spatial filtering; the cost-effective fabrication of high-quality, large-aperture optics; and the development of automatic control systems. We have simulated many preliminary versions of the Nova laser chain and have selected most of the features that will appear in the final Nova design. This laser system is now envisioned as a two-phase project beginning in fiscal year 1978. The first phase is expected to begin operation at about 100 TW in 1982 with a second phase at 200 to 300 TW to be operational in late 1983.

CONCLUSION

We have advanced neodymium–glass laser technology from the 0.1-TW level to above 20 TW and are aiming for the 200- to 300-TW range, more than a thousandfold increase in performance. This rapid progress in laser technology has come about because we have been able to integrate physics experiments, computer modeling, component design, and system development. We have not yet ex-

hausted the possibilities in solid-state laser technology. Already, new ideas in laser design indicate that 10-MJ, 1000-TW systems may be feasible. Recent studies also point the way to high pulse-repetition-rate systems with greatly improved efficiencies.

Key Words: Argus laser system; Cyclops; Janus; neodymium-glass; Nova; Shiva; spatial filters.