NOVA LASER FUSION FACILITY–DESIGN, ENGINEERING, AND ASSEMBLY OVERVIEW

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The Nova laser fusion research facility, currently under construction at Lawrence Livermore National Laboratory (LLNL), will provide researchers with powerful new tools for the study of nuclear weapons physics and inertial confinement fusion (ICF). The Nova laser system consists of ten large (74-cm-diam) beams, focused and aligned precisely so that their combined energy is brought to bear for a small fraction of a second on a tiny target containing thermonuclear fuel (deuterium and tritium). The ultimate goal of the LLNL ICF program is to produce fusion microexplosions that release several hundred times the energy that the laser delivers to the target. Such an achievement would make ICF attractive for military and civilian applications.

The U.S. Department of Energy has approved construction of ten Nova laser beams, harmonic-conversion crystal arrays, and the associated laboratory buildings. By the mid 1980s, Nova will produce the extremes of heat and pressure required to explore the physical region of ignition of the thermonuclear fuel. Additional developments in the area of high-efficiency drivers and reactor systems may make ICF attractive for commercial power production.

INTRODUCTION

One technical approach to the problem of controlling thermonuclear fusion reactions is to bring small deuterium-tritium (D-T) fuel pellets to very high temperatures and densities in such a short time that the thermonuclear fuel will ignite and burn before the compressed core disassembles. This approach, known as "inertial confinement," relies on a driver (e.g., a laser) to deliver the extremely high-power short-duration burst of energy required.

The objectives of the national inertial confinement fusion (ICF) program are twofold: in the short term, to develop the military applications of ICF, and in the long term, to evaluate ICF as an energy source.[1,2] At Lawrence Livermore National Laboratory (LLNL), our immediate scientific objectives are the demonstration of high compression (100 to 1000 times liquid D-T density) and exploration of the required ignition of thermonuclear burn. These achievements are necessary precursors to the successful realization of either the military or the energy objectives of the program. From a technical point of view, the ignition milestone is very important.

Solid-state neodymium-glass lasers have been chosen for experimental driver systems because that particular technology was most advanced at the time the decision was made. Over the past several years, a series of increasingly powerful and energetic laser systems has been built to study the physics of ICF targets and laser/plasma interactions. Nova, the latest in this series, is the successor to the Argus[3] and Shiva[4] lasers. The Nova laser will consist of ten beams, capable of concentrating 100 to 150 kJ of energy (in 3 ns) and 100 to 150 TW of power (in 100 ps) on experimental targets by 1985. Nova will also be capable of frequency converting the fundamental laser wavelength (1.05 μm) to its second (0.525 μm, or green) or third (0.35 μm) harmonic. This additional capability (80 to 120 kJ at 0.525 μm, 40 to 70 kJ at 0.35 μm) was approved by the U.S. Department of Energy (DOE) in April 1982. Since these shorter wavelengths are much more favorable for ICF target physics,[5] Nova's ability to explore the region of ignition of thermonuclear burn is greatly enhanced. ["Ignition" implies density and pressure conditions such that the alpha particles in the central core of the compressed fuel are trapped, thus heating the remaining (cooler) fuel.]

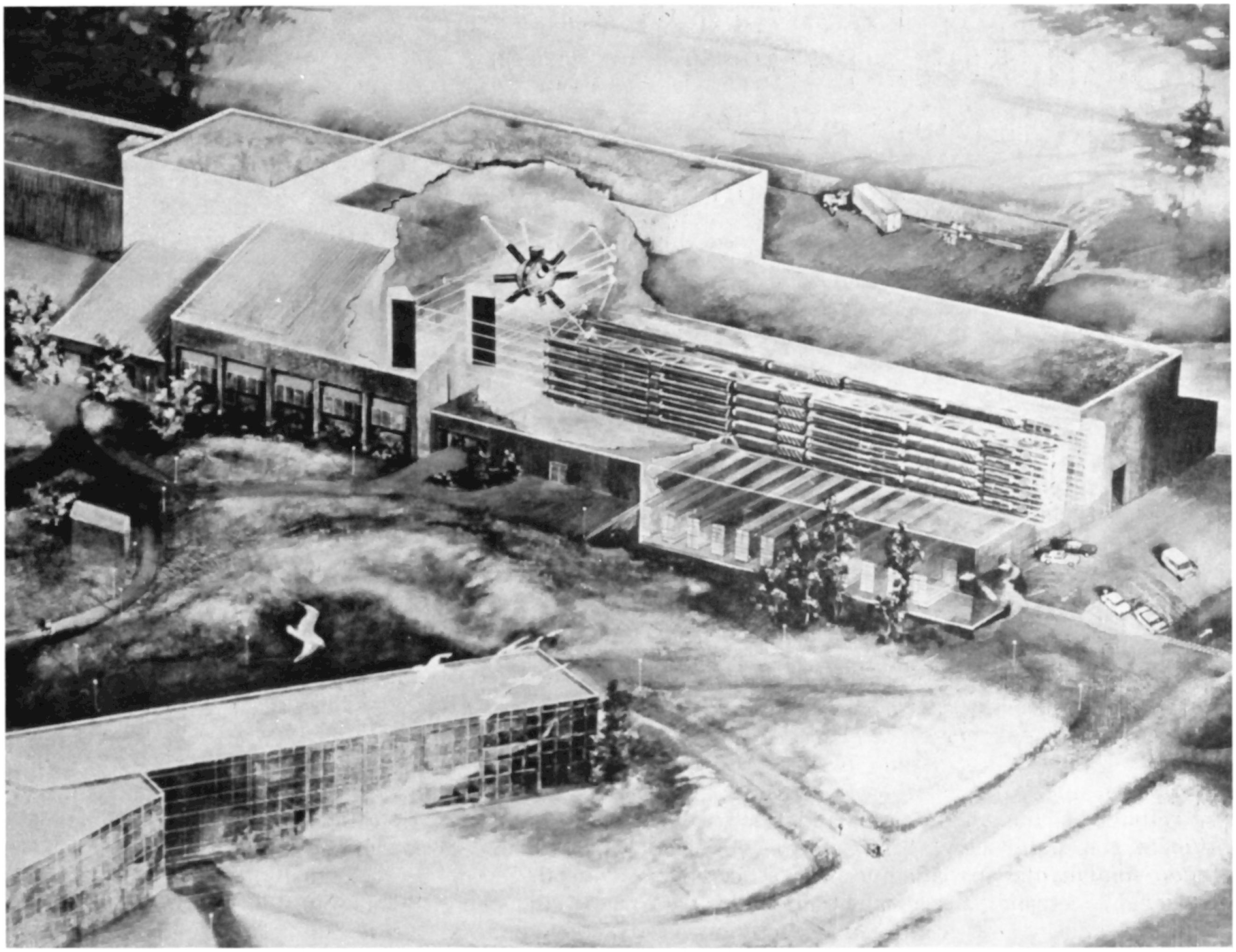

Fig. 1. The Nova laser fusion facility for exploration of the physical regime of ignition of advanced thermonuclear fuel targets.

An artist's cutaway drawing of the Nova layout is shown in Fig. 1. The conventional construction segment of the Nova project, the 115 000-ft^2 laboratory building in which the ten-beam neodymium-glass laser system will be installed, was completed in June 1982. The ten beams from the laser are brought with high-reflectivity mirrors to an integrated target chamber in two opposed clusters of five beams each. Frequency conversion is accomplished with potassium dihydrogen phosphate (KDP) crystal arrays, mounted just in front of the fused silica focusing lenses on the target chamber vessel. The 50-MJ capacitor bank, which powers the system flashlamps, is directly below the laser. The total cost of the Nova project will be $176 million when it is completed in the autumn of 1984.

In this paper, we present laser design and performance estimates, and discuss preliminary confirmation of these estimates from a target irradiation system, called "Novette",[6] which currently comprises the first two Nova beam lines. We then present an overview of some of the key laser components and a discussion of frequency conversion with large aperture KDP arrays. We conclude with an overview of the sophisticated subsystems—power conditioning, alignment, diagnostics, controls, and data acquisition—that will support the laser system as an integrated experimental facility. A more detailed description of these subsystems, their design, and their interrelationships can be found in Ref. 7.

LASER DESIGN AND PERFORMANCE

The Nova laser system has master-oscillator-power-amplifier architecture. As shown schematically in Fig. 2, a laser pulse of requisite temporal shape is generated by the oscillator,[8] preamplified, and split into ten beams. After traversing an adjustable optical delay path (used to synchronize the arrival of the various beams at the target), the pulse enters

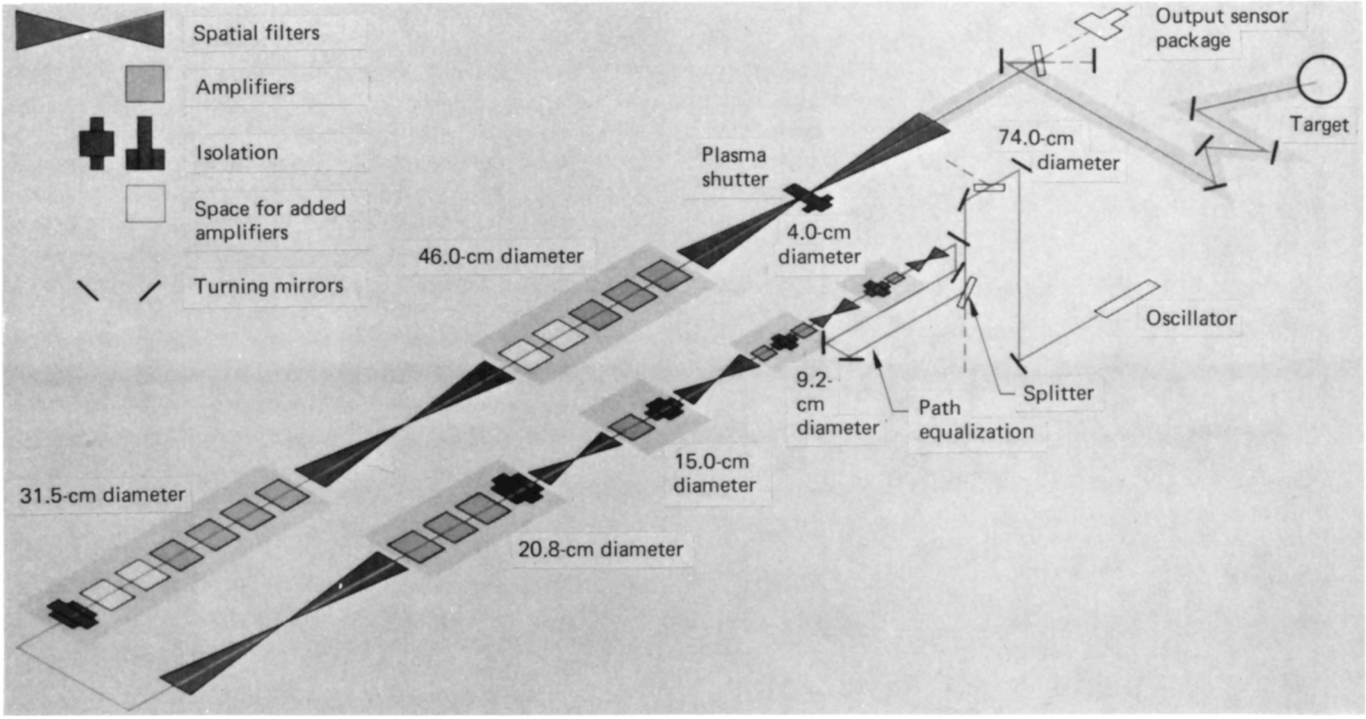

Fig. 2. Schematic diagram showing the major optical component locations for one of the ten Nova beam lines.

the amplifier chain, where (a) rod and disk amplifiers increase the pulse power and energy, (b) spatial filters maintain the spatial smoothness of the beam profile while expanding its diameter, and (c) isolators prevent the entire laser from breaking spontaneously into oscillations that could drain its stored energy and damage the target prematurely.

The beam is collimated between spatial filters in the laser chain. Thus, each of the components in a particular section has the same diameter. In the 4.0-cm section (see Fig. 2), the amplifier is a single glass rod, and the isolator is an electro-optic (Pockels) cell crystal placed between crossed polarizers. This cell operates as a fast (10-ns) optical gate, preventing interchain oscillations and at the same time reducing to tolerable levels unwanted amplified spontaneous emission (i.e., radiation at the laser wavelength, amplified by passage through the chain, which can strike and damage the target before the laser pulse arrives). In all larger diameter sections, the amplifiers consist of face-pumped disks set at Brewster's angle to the passing beam. Polarization-rotating isolators, relying on the Faraday effect,[9] assure intrachain isolation. Most of the Shiva laser components will be reused in Nova.

Optimum spatial filter design provides entrance-lens-to-entrance-lens imaging.[10] Thus, smooth beam intensity (through the cross-sectional area) is projected along the chain, and energy extraction by the laser pulse is maximized. The beam has a filling factor of >80% (defined as the ratio of the integral of the beam energy density over its spatial profile to the energy in a uniformly distributed beam of the same aperture). Pinholes (located at the spatial filter focal planes) are large enough to avoid self-closure (due to the ablation of material around the pinhole edge) during the passage of the pulse. The longest spatial filter in the Nova chain is 23 m (75 ft) long. It is located between the final laser amplifier and the optical turning mirrors.

When the pulse exists from the final beam-expanding spatial filter, it has been amplified to an energy level of 10 to 15 kJ, and its diameter is 74 cm. Turning mirrors direct the beam to the target chamber, where focusing lenses concentrate it on the target. The first of the turning mirrors is partially transparent, allowing ~2% of the pulse to enter the output sensor package. This unit senses and reports on the alignment status, energy and power, spatial quality, and other characteristics of the beam. The plasma shutter, located at the focal position of the final spatial filter, protects the laser by preventing light reflected from the target from reaching the laser amplifiers. In the absence of this protection, such light would travel back down the chain (being amplified in the process), and possibly destroy some of the optical components.

In each section, the beam is amplified to the damage threshold of the lenses at a maximum energy output for a specified pulse duration. This "isofluence" design maximizes the energy output per unit cost, while keeping the chain as a whole below the optical component damage limit. The fluence (energy per unit area) at which optical components suffer damage clearly limits the energy and power output from a fixed-aperture laser amplifier chain. Consequently, it has been the subject of intense investigation and development throughout the country.[11]

The components likely to suffer damage in the current Nova chain design are: (a) spatial filter entrance lens surfaces, (b) high-reflectivity turning mirror coatings, (c) KDP crystals, and (d) fused silica antireflecting surfaces on focusing lenses and crystal array windows. A proprietary graded-index treatment of silicate glass surfaces known as "neutral solution processing" (NSP) has been developed.[a] This process will be used as an antireflecting surface treatment for the spatial filter lenses, since it has proven to be highly resistant to damage.[12] The turning mirrors are coated for high reflectivity at 1.05 μm with dielectric films of alternating high- and low-index oxides. Mirror coatings and KDP crystals have also shown improved resistance to fluence damage with a process called "laser hardening."[13] Fused silica surfaces must be antireflecting at both 0.525 and 0.35 μm, as well as possess relatively high damage resistance. Unfortunately, NSP is not applicable to fused silica. A graded-index surface treatment that shows great promise for this application is under development. Damage thresholds to which Nova has been designed are listed in Table I. Threshold dependence on pulse duration is well approximated by a square root law, so long as the surfaces are scrupulously free from absorbing contaminants.

Figure 3 gives an example of expected performance at the damage limits shown in Table I (for a nominal 1-ns pulse). The location of each spatial filter lens in the chain is shown at the top of the figure. The solid line represents the peak fluence at each lens, and the dark points represent the average fluence at each lens. Both peak and average fluences increase as the pulse passes through the various amplifier sections between spatial filters. Average fluence grows as a result of amplification of the pulse energy. However, the peak fluence grows faster because it is also affected by nonlinear self-focusing and spatial noise sources (discussed below). Beam-expanding spatial filters reduce both the average fluence and the peak-to-average ratio. The design laser can focus >10 kJ per beam on the target in a 1-ns pulse before any component is threatened. This per beam capability approximates that of the entire Shiva system.

Calculations such as those described above have been performed over the temporal range (0.1 to 3 ns) for the baseline Nova chain. Results are summarized in Fig. 4. The upper curve represents hypothetical single-chain performance at the first-component-to-damage limit if a perfectly smooth beam were to pass through it. However, real beams exhibit spatial modulation as a result of imperfections encountered upon passage through optical components. Therefore, realistic performance levels must be set on the basis of the peak-to-average intensity ratio of the beam at the location of the threatened component. Computer estimates thus lead to the lower curve, which represents an upper limit on performance of the

TABLE I

Fluence Damage Threshold for Critical Nova Components

Component	Damage Threshold (J/cm²) at: Pulse Duration (ns) 0.1	1.0	3.0
NSP lenses at 1ω	5.5	17	30
High-reflectivity mirror at 1ω	3	10	15
KDP crystals at 1ω	3	9	16
Graded-index silica at 3ω	---	(4+)	---

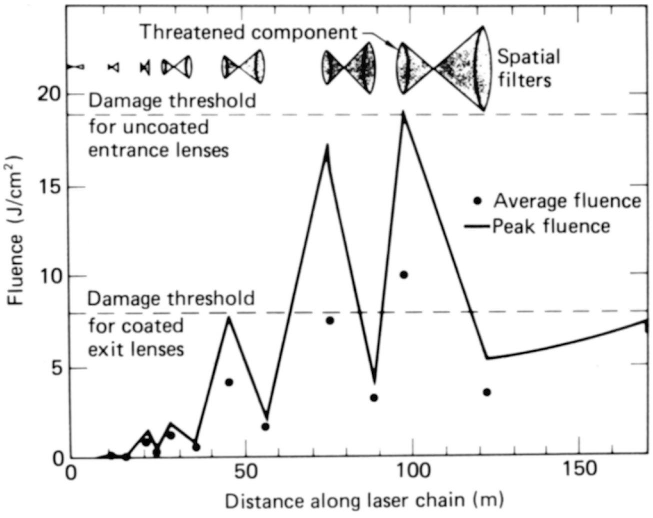

Fig. 3. Interchain peak and average fluences as a function of distance along the laser chain for a 10.5-kJ 1-ns laser pulse. Location of spatial filter lenses is indicated along the top of the figure. Entrance lens surfaces will suffer damage if the peak fluence exceeds the indicated limit.

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[a] The developer is Schott Optical Company, Duryea, Pennsylvania.

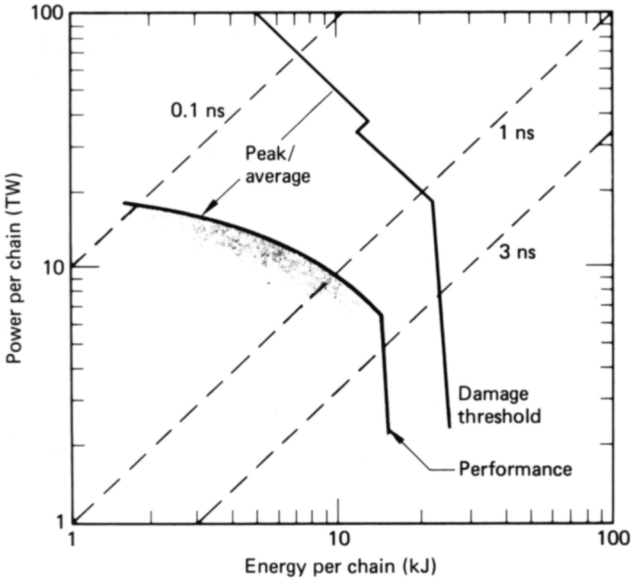

Fig. 4. Performance limits over the full temporal design range of Nova. The laser can be operated without incurring optical damage to any component within the shaded region.

laser at any pulse duration. In the case of long pulses, nonlinear effects become less important. Therefore, the ratio of input to output peak fluences at the spatial filters approaches the geometric expansion ratio. The KDP array and focusing lens tend to be the limiting elements for long pulse performance. In the case of very short pulses, nonlinear growth of spatial peaks along the propagation path from the output of the last spatial filter could also damage the final components.

Space has been allocated in the 31.5- and 46.0-cm sections for additional amplifiers. Currently, it appears feasible to procure and install amplifiers there, thus increasing Nova performance at very modest cost. This option is under serious consideration.

The computations illustrated in Figs. 3 and 4 were performed using the fast Fourier transform code[14] MALAPROP, which (a) accurately simulates detail beam propagation through spatially filtered amplifier chains, (b) accounts for the performance of the Argus and Shiva systems, and (c) confirms the spatial filtering strategy for the larger Nova system. The predictive success of this comprehensive code is primarily a result of its spatial noise model, which correlates well with independent statistical observations of noise sources.[14]

The MALAPROP code sequentially calculates the evolution of a spatially profiled pulse as it passes through the various elements of a laser chain. Spatial filtering and free-space propagation between elements are modeled by means of two-dimensional fast Fourier transform algorithms. Nonlinear media (e.g., glass) are represented as phase transformations. In the model, all glass components are treated as "thin." Pinholes in spatial filters are modeled by aperture truncation in the Fourier transform plane of each spatial filter entrance lens.

The full two-dimensional 512 X 512 mesh version of MALAPROP is used to assess nonlinear spatial noise growth and pinhole filtering for beam diameters as large as those required for Nova. A longer running version of MALAPROP is available to model the effect of amplifier gain saturation[15] on a local scale throughout the laser chain. (This effect is important for temporally long high-energy pulses.) An example of this more detailed calculation is shown in Fig. 5. Experimental results with longer pulses (and split beams) have been amply supported by such calculations.

In practice, the code calculates (on the basis of fixed laser chain staging and input power) the peak intensity at each lens in the system, the intensity at the perimeter of the spatial filter pinholes, and the intensity distribution in the final or target lens focal plane. Quantitative knowledge of these parameters is crucial in evaluating the relative merits of different spatial filter staging strategies. In addition, pinhole diameters are chosen such that beam intensities on their perimeters are not $>10^{11}$ W/cm^2 (an intensity below threshold for plasma formation). Focal spot blurring is also estimated.

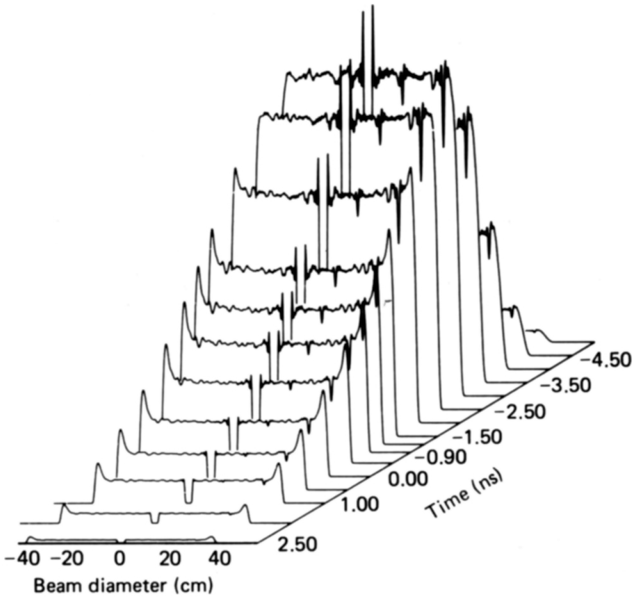

Fig. 5. Full computer simulation of a 12.8-kJ 3-ns Nova beam profile as it appears entering the frequency conversion array. Profiles shown toward the back of the figure arrive at the target earliest in time.

All major laser systems are ultimately limited by small-scale spatial fluctuations, which originate from optical imperfections in the components or on their surfaces. We have introduced a spatial-noise-source model that accurately mimics the effects of small scattering sites (~200 μm in diameter) located primarily on disk surfaces. Points (or point clusters) are set to zero at random locations on the MALAPROP computational grid, thus representing opaque particles or "obscurations." From careful laboratory examination of disk amplifiers and other sources, the number and size distribution of these obscurations are characterized. The parameter that best correlates system performance with obscuration count statistics (based on comparison between MALAPROP results and Argus and Shiva experimental data) is the fractional obscured area per disk surface (typically 5×10^{-5}). We have used this numerical parameter in our simulations of Nova performance and as a design criterion for the surface quality of the Nova disks. Scrupulous attention to clean amplifier assembly, maintenance, and operation is required to achieve this degree of perfection.

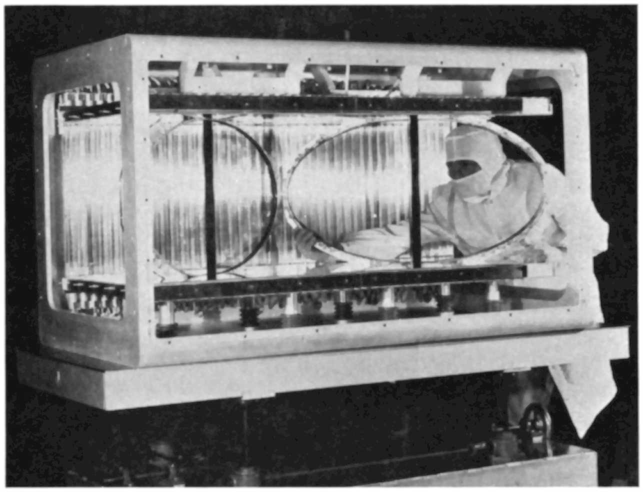

Fig. 6. Partially assembled 46-cm rectangular laser disk amplifier. Transverse flashlamps and their reflectors appear behind the elliptical half-disks. Optical cavity interior parts are silver-plated for high reflectivity.

COMPONENTS: AMPLIFIERS

Disk amplifiers and other components with apertures of 21 cm or less are typical of Shiva-based technology.[4] The larger Nova amplifiers feature a rectangular[16] internal geometry (as opposed to cylindrical) that permits flashlamps to pump the laser disks more efficiently. A side view of a partially assembled 46-cm rectangular amplifier is given in Fig. 6. Flashlamps will run along two opposing sides of the rectangular case, facing the installed disks. Each flashlamp is backed by a silver-plated crenulated reflector, which reflects light into the disk faces while minimizing absorption by neighboring flashlamps. An electroform process is used to manufacture these reflectors. Flat, silver-plated walls form the remaining two sides. The cavity is very reflective and will provide tight optical coupling of light from flashlamps to disks. Careful design has made possible efficiency improvement of a factor of 2 over the cylindrical amplifiers used in the Shiva laser system.

Maintenance of the high surface quality of the disks is extremely important. For this reason, flat transparent glass shields will be used to isolate the disks from the flashlamps. The shields also prevent serious degradation of the quality of the beam by keeping thermal disturbances formed in the atmosphere around the flashlamps from penetrating the optical beam path. Rectangular disk amplifiers are employed in the final three amplifier sections of Nova. Design criteria have been met in component tests and are summarized in Table II.

Phosphate-based glass[17] features very high intrinsic gain, as well as sufficient energy storage capacity for the realization of Nova laser performance goals. Furthermore, it has proven to be manufacturable in

TABLE II

Nominal Design Criteria: Nova Rectangular Disk Amplifiers

Amplifier Aperture Diameter (cm)	Number of Disks	Disk Thickness (mm)	Stored Energy in Bank (kJ)	Number of Lamps	Nominal Small Signal Gain
20.8	3	30	200	16	2.30
31.5	2	43	375	20	1.80
46.0	2 (split)	43	600	80 (transverse)	1.75

large sizes to Nova specifications relating to optical quality and resistance to damage.[b] A condensed table of significant optical parameters for this glass appears in Table III.

With disks of large diameter, the gain path for internally generated amplification of spontaneous emission (ASE) becomes longer. Internal ASE represents a parasitic drain[18] on the energy stored in each disk. At the largest Nova amplifier diameter (46 cm), drastic measures must be taken to suppress this drain. This is the reason the disks are split along their minor diameters. Much higher energy storage and gain can be realized from a 46-cm-diam disk when it is split as shown in Fig. 6. For Nova, each disk half is completely surrounded by a "monolithic" edge cladding bonding, manufactured with glass that is thermally and mechanically compatible with phosphate-based laser glass. This edge cladding serves two purposes. First, it has the same index of refraction as the laser glass, so that reflections of the internal amplified spontaneous emission that could reenter the disk and undergo further parasitic amplification are minimized. Second, because it is doped with copper ions, it strongly absorbs energy at the laser wavelength (1.05 μm), serving as a "sink" for unwanted energy. These claddings represent a significant improvement on conventional (frit) claddings employed on previous laser disks.

Naturally, a split disk produces a split beam, and although diffraction effects originating at the split can be diminished by careful beam shaping (apodization) techniques, residual edge modulation due to diffraction still remains (see Fig. 5). Nevertheless, at beam apertures greater than ~40 cm, the cost and performance benefits of split disks far outweigh diffraction problems.

COMPONENTS: ISOLATORS

Historically, Faraday rotator-polarizer combinations have been used as isolators to protect the laser from reflected target light. However, these become very expensive as their size increases, because of the cost of the terbium-based glass and energy storage required. Faraday isolation at the final amplifier aperture of Nova would cost approximately $800 000 per beam. The plasma shutter[19] represents an alternative, less costly solution.

In concept, the plasma shutter consists of a wire (or foil) metallic sample closing an electric circuit. This circuit stands ready until the optical pulse has passed the pinhole at the final spatial filter. At that instant, an electrical surge large enough to sublimate the foil is applied. This creates a plasma jet, which is directed transverse to the beam path near the pinhole. The driving current pulse must be very rapid to create the plasma, which blocks light reflected from the target, since this light reappears at the plasma within ~400 ns. Consequently, advanced rail-gap technology has been used to minimize electrical circuit inductance. Tests have confirmed that the 3 cm/μs plasma velocity created with an energy store of 6 kJ is sufficient to ensure closure.

TABLE III

Optical Characteristics of Neodymium-Doped Phosphate Laser Glass

Peak stimulated emission cross section	4.0×10^{-20} cm^2
Peak fluorescence wavelength	1.053 μm
Refractive index	1.52
Effective linewidth	26 mm
Calculated radiative lifetime	338 μs
Nonlinear refractive index coefficient (γ)	2.89×10^{-20} m^2/W

Three criteria must be satisfied by the plasma shutter driver circuit. First, the plasma jet must be sufficiently dense to block all of the light returning from the target. To ensure this, we generate a plasma of greater than critical density (for 1.05-μm light). Second, the plasma shutter must operate in the vacuum surrounding the spatial filter pinhole. To be useful for system applications, it must work reliably for many shots. This has been accomplished with a novel foil-chip changer, which replaces the used foil with a fresh one after every shot. Third, the plasma formed by the 1-MA electrical pulse must be directed so that no debris accumulates at the spatial filter lenses. This is done by carefully shaping the foil (and the changeable chip in which it resides) prior to the application of the electrical pulse. All debris from the exploding foil is captured at a plasma dump located transverse to the beam propagation direction. The entire unit, including its control electronics, pulse-forming network, and power supplies, will be located adjacent to the final spatial filter. Electromagnetic interference with system electronics in the Nova test facility poses no major problems based on prototype testing in Shiva. This unit is significantly cheaper than the equivalent Faraday rotator-polarizer combination; also it has no optical losses.

COMPONENTS: OPTICS

Nova may well be the largest precision optical project ever undertaken. Moreover, during the course of construction, concurrent R&D has been successfully conducted, and has resulted in significant

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[b] Manufactured by Hoya Optics, Fremont, California, and Schott Optical Company, Duryea, Pennsylvania.

TABLE IV

Optics for the Nova Laser

1000 major optical components
2000 ℓ of laser glass
1000 ℓ of fused silica
10 000 ℓ of borosilicate glass
150 ℓ of KDP crystals
200 m^2 of optical quality surfaces
100 m^2 of optical thin film coating
1.1-m single piece maximum diameter
380-kg single piece maximum weight
0.06-μm average optical surface accuracy

advances in various technical areas, including manufacturing efficiency. Optical production, including construction of the special facilities required for many of the components, has been under way for >5 yr, and many phases of the optical manufacturing program will be completed within the next 2 yr. In addition, new requirements for second and third harmonic generation have created a need for further R&D. Some statistics illustrating the massiveness of the project are shown in Table IV.

In terms of beam-handling components, for example, the ten-beam laser contains 38 mirrors between 0.8 and 1.1 m diameter, with front surface accuracies of better than $\lambda/12$ at 633-nm wavelength. (This represents flatness to within 2 μin.) Some of the borosilicate glass blanks, from which these mirrors are fabricated, are shown in Fig. 7.[c] A coated mirror is shown in Fig. 8.[d] Also, because these optical components weigh several hundred pounds each, special handling equipment has been designed for assembly on the Nova laser system.

Fig. 7. Borosilicate glass blanks for the Nova turning mirrors.

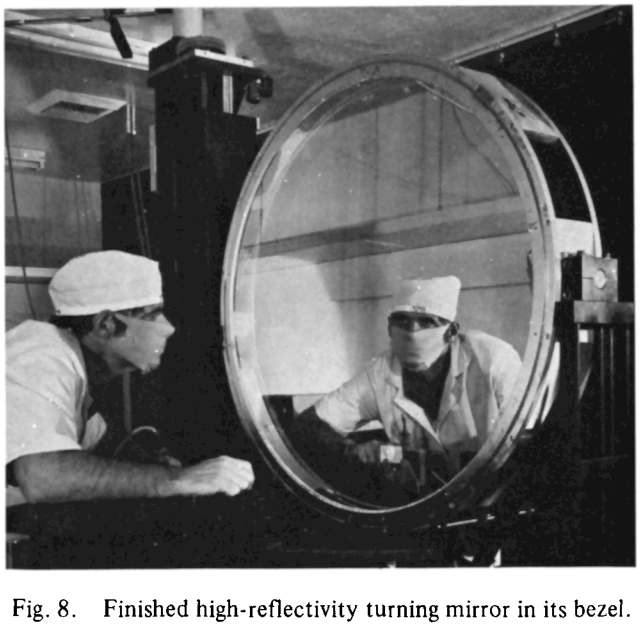

Fig. 8. Finished high-reflectivity turning mirror in its bezel.

FREQUENCY CONVERSION AND TARGET FOCUSING

Potassium dihydrogen phosphate (KDP) is one of a class of insulating crystals that are suitable for frequency conversion of optical radiation.[20] KDP possesses no center of symmetry; it is uniaxially birefringent; and it is highly transparent over the entire visible spectrum. Birefringence in the current context implies that light travels through the crystal with a phase velocity that depends on its linear polarization and propagation directions. Therefore,

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[c] Schott Optical Co., Duryea, Pennsylvania; Eastman Kodak, Rochester, New York; Zygo Corporation, Middlefield, Connecticut; Tinsley Laboratories, Berkeley, California; and Perkin-Elmer Corporation, Norwalk, Connecticut, have contracted to finish these and other large optics.

[d] Coating for high reflectance at 1 μm will be done by Optical Coating Laboratory, Inc., Santa Rosa, California, and by Spectra Physics, Mountain View, California.

by properly choosing these directions, the phase velocities of two wavelengths of light (e.g., the fundamental and the second harmonic) can be matched precisely. This so-called "phase-matching" technique[21] can be used to convert light of one wavelength to its second harmonic with high efficiency, in theory, approaching 100%. It is applicable to "frequency mixing" as well.

For Nova, this means that 1.05- and 0.525-μm light, impinging on a KDP crystal with correct polarizations and propagation directions relative to the crystalline axes, will convert with high efficiency to 0.35-μm light (the third harmonic). The phase-matching technique for optical frequency conversion and frequency mixing is currently in routine use in many laboratories throughout the world.[e]

KDP, in addition to its very suitable optical properties, is capable of being grown from water solution to substantial sizes. Figure 9 shows boules from which 27-cm-square crystals will be cut.[f] Growth of these boules from their seed crystals requires several months of continuous growth under carefully controlled conditions.

Once grown and rough cut, the KDP crystal surfaces must be precisely finished to exacting angular and linear tolerances. Experiments at LLNL determined that diamond-turning was a feasible approach to machining of this material. KDP diamond-turning technology has currently been proven with full-sized crystals,[g] such as shown in Fig. 10, which have been assembled and are currently in use as frequency doublers in the Novette laser.[6]

Once finished, the KDP crystals are assembled into a 3 X 3 array, whose total clear aperture is 77 cm. The prototype assembly, used in Novette, is shown in Fig. 11. The Nova crystals will be supported in "sandwich" fashion between transparent windows of fused silica. The interfaces between KDP and silica are filled with a thin (~10-μm) layer of halocarbon fluid to minimize reflection losses at surfaces of differing refractive index. The windows are supported internally with a precision-finished crate-like structure. A partial vacuum within the array assembly allows atmospheric pressure to

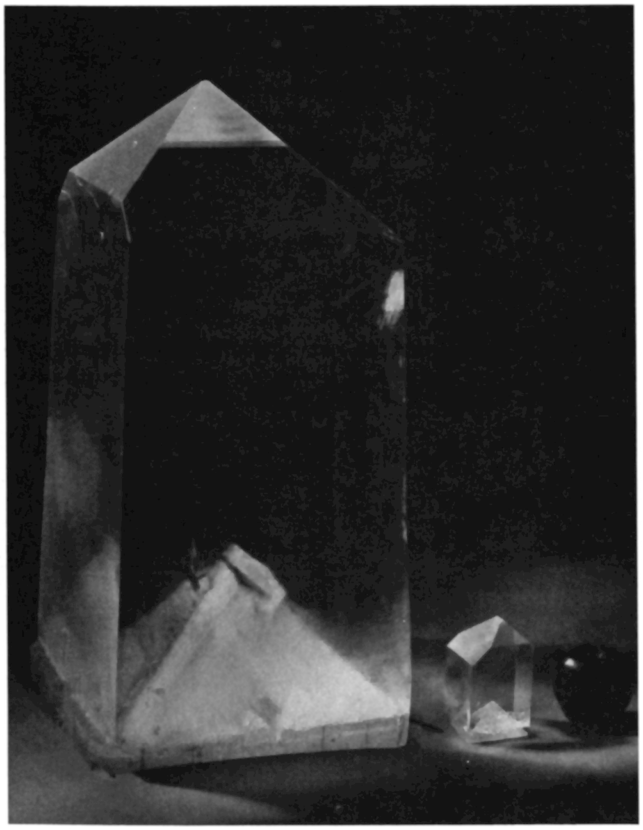

Fig. 9. 27 cm X 27 cm KDP crystal boule.

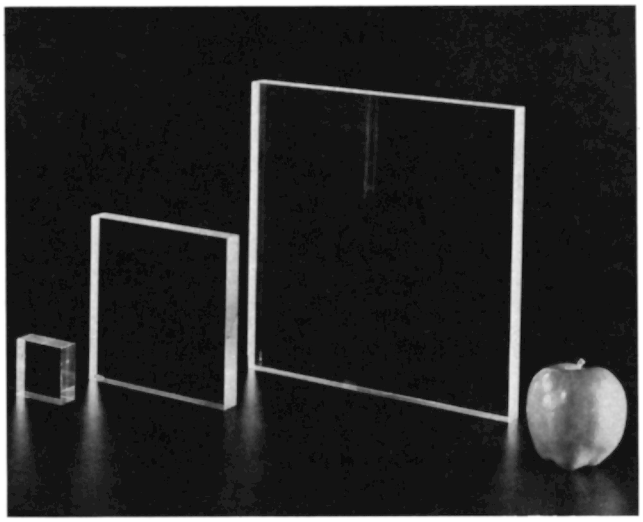

Fig. 10. Oriented and finished KDP crystals. These crystals were single-point diamond turned to produce extreme surface flatness and face parallelism.

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[e] Laboratories active in laser fusion research, in addition to LLNL, include the following: Laboratory for Laser Energetics, University of Rochester, Rochester, New York; Naval Research Laboratories, Washington, D.C.; KMS Fusion, Inc., Ann Arbor, Michigan; Los Alamos National Laboratory, Los Alamos, New Mexico; Rutherford Laboratories, Great Britain; Commissariat à l'Energie Atomique, Limeil, France; the Lebedev Institute, Moscow, USSR; OSAKA University, Osaka, Japan.

[f] Currently, Cleveland Crystals, Cleveland, Ohio, and Interactive Radiation, Northvale, New Jersey, are under contract to produce the 27-cm square crystals.

[g] Cleveland Crystals, Cleveland, Ohio, and Pneumo Precision, Keene, New Hampshire, are currently under contract to finish the Nova KDP crystals.

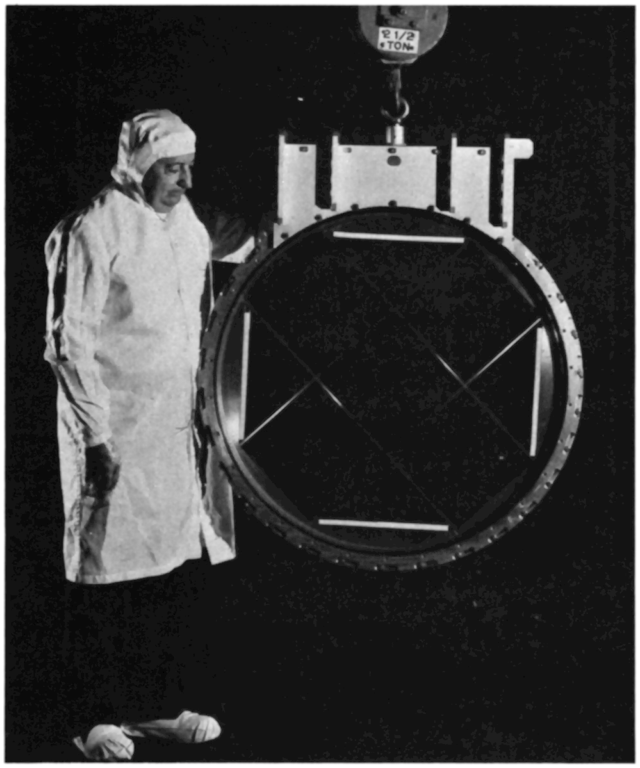

Fig. 11. Assembled frequency doubling array, currently producing >6 TW of power at 0.53 μm when driven with 12 TW of 1.05-μm laser light from Novette.

maintain the windows snugly and evenly against the internal supports. Wavefront aberrations of the assembled array are on the order of one to two waves at 1 μm in transmission.[h]

A system capable of producing both second and third harmonics over a wide range of input intensities, employing two identical crystal arrays in optical series, has been developed.[22] Conventional approaches to this problem would require three different crystal assemblies (i.e., three different crystal lengths), significantly increasing the cost and reducing the commonality and interchangeability of parts. In this design, second-harmonic generation is achieved using two Type II 1.0-cm-thick 74-cm aperture KDP crystal arrays operating in series. The two arrays are oriented so that they function independently, producing second-harmonic light in two orthogonally polarized components, one from each array. The major feature of this design is the wide input intensity range over which high-conversion efficiency can be maintained. This is illustrated in Fig. 12.

Third-harmonic generation is easily achieved because the two crystal arrays are already in the

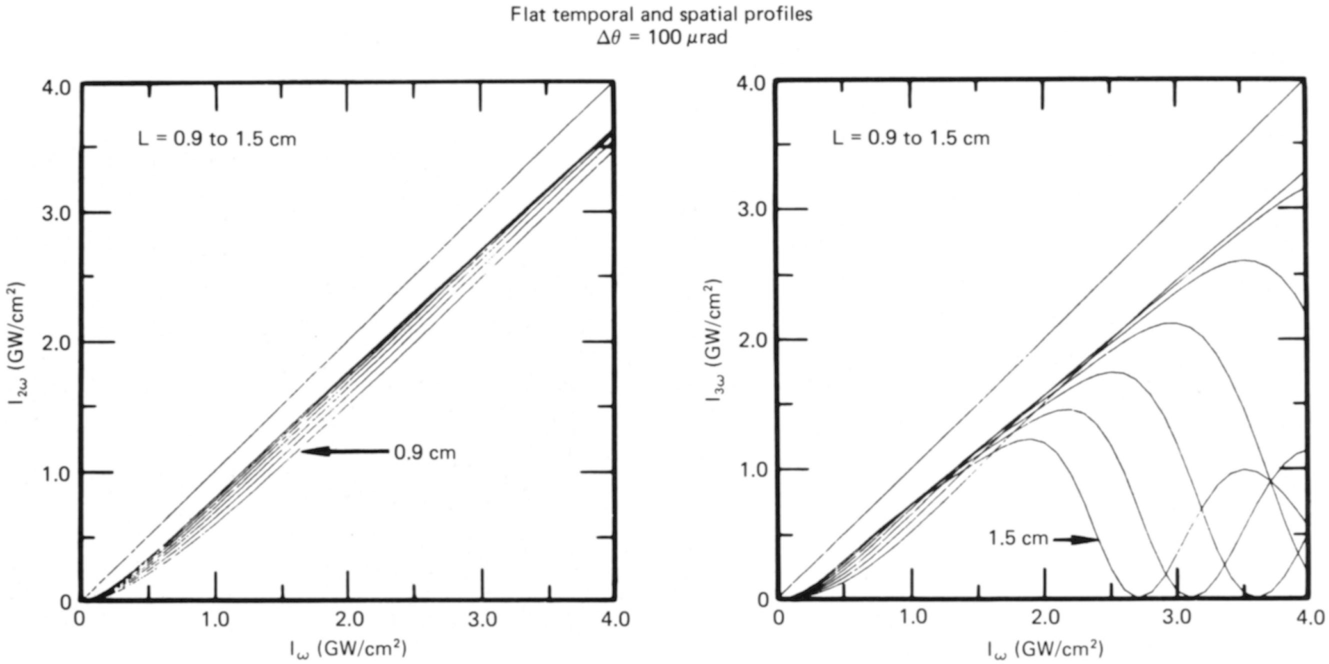

Fig. 12. Second- and third-harmonic output intensity versus fundamental input intensity for a range of crystal thickness choices; quadrature second-harmonic/tandem third-harmonic scheme, both crystals of equal thickness. Note the extremely large dynamic range of the second-harmonic transfer curve on the left.

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[h] Fused silica for the array windows and for the focus lenses is being supplied to Nova under contracts with Corning Glass Works, Corning, New York, and Heraeus Quartzschmelze, Hanau, Federal Republic of Germany.

basic orientation for the "Type II–Type II polarization mismatch" configuration analyzed by Craxton[23] and demonstrated by Seka et al.[24] Proper alignment is accomplished simply by rotating the assembly about the beam direction by 10 deg and angle tuning the second crystal (only one axis of the assembly) onto the mixer phase-matching angle ($\Delta\theta \simeq 6$ mrad). Efficient conversion is achieved over a somewhat smaller input fundamental intensity range than for second-harmonic generation. The design is optimized for a fundamental drive intensity of 2.5 GW/cm^2, spanning the Nova pulse width range of 1 to 3 ns. This operating range is consistent with other system constraints; i.e., those imposed by nonlinear propagation and by material fluence damage limits.

Multi-wavelength capability is therefore realized by identical crystal cut and configuration. High efficiency is achieved by optimizing the crystal lengths for the input intensity range of interest. For commonality of parts, both arrays use identical crystal lengths. Analysis indicates that this can be done with no performance penalty.

In Fig. 13, performance expectations for one of the Nova chains, and for the three wavelengths of interest, are shown over the full temporal range of interest. System operation is possible without component damage in regions to the lower left of each curve. The 1.05-μm curve reproduces that of Fig. 4, and is representative of drive levels available to the frequency conversion array. Third-harmonic performance at 0.35 μm is power-limited by nonlinear growth of irregularites on the wavefronts as they propagate through the fused silica window and focusing lens.

In Fig. 14, an artist's concept of the array and focusing lens is shown, as it (conceptually) mounts to the target chamber. This focusing lens must also serve as the vacuum barrier. Alignment aids (crosshair and retro-reflector, both retractable from the beam line during shots) are also shown. The optical train for frequency conversion and beam focusing is very simple; it is shown schematically in Fig. 15. A dichroic beam dump (not shown in Fig. 14) transmits only the wavelength desired for a particular experiment. Dispersion in the fused silica focus lens causes different wavelengths to focus at different distances from the lens, as shown. Therefore, a target at or near the focal position for the desired wavelength lies in the shadow of the beam dump for remanent wavelengths. Care must be exercised in the placement of the crystal array relative to the focus lens to avoid having "ghost" foci (back reflections from the lens surfaces) located within the crystals; this spacing is currently ~1.0 m. The shield is required to protect the focus lens from debris originating in the disintegration of the target itself;

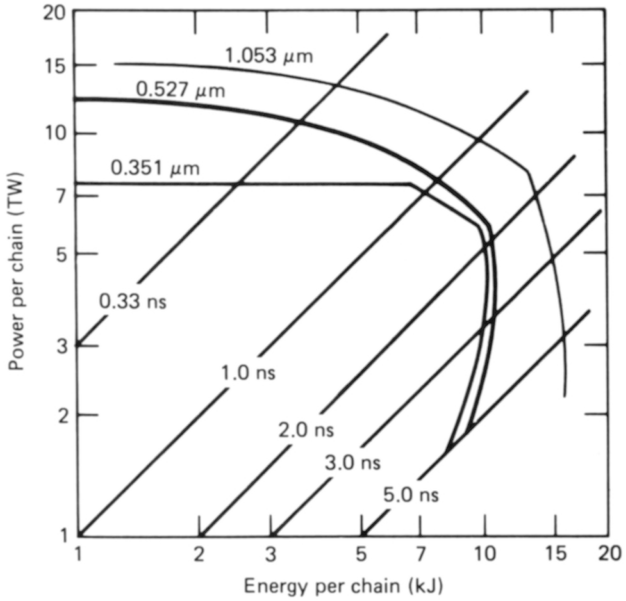

Fig. 13. Nova single chain performance limits for second- and third-harmonic operation. The fundamental curve is reproduced from Fig. 4, and has the same significance in this figure.

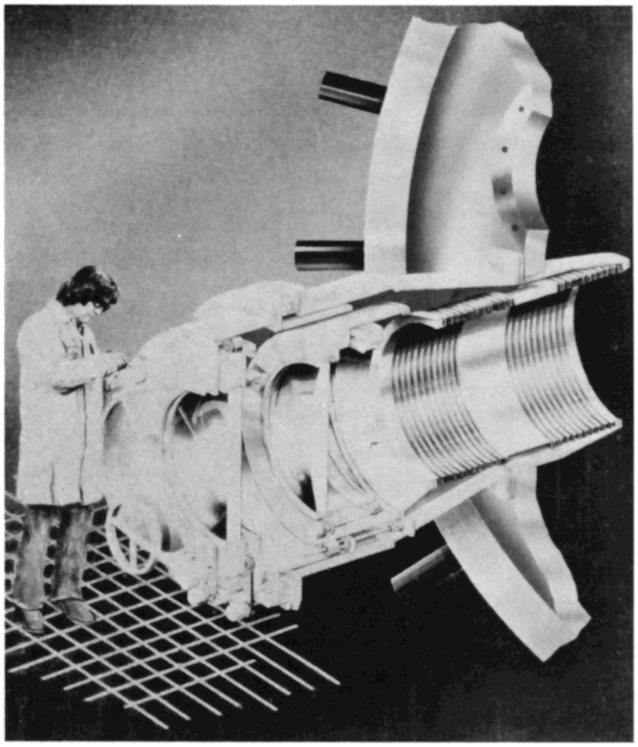

Fig. 14. Artist's conception of the component arrangement comprising the frequency conversion array and the fused silica focusing lens. The aperture is 74 cm; the effective focal length of the lens is 3 m.

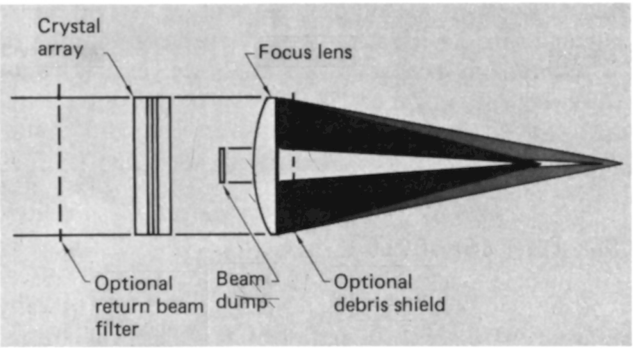

Fig. 15. Optical schematic illustrates the focusing optics/frequency conversion strategy for irradiating targets with single-color light. The return beam filter absorbs third-harmonic light, thereby protecting the beam transport optics and turning mirrors from solarization. The multichroic beam dump absorbs unwanted wavelengths; the target can be located in its shadow.

Fig. 16. Focus lens drive mechanism in final assembly.

such debris would otherwise seriously degrade the transmission of the lens after only a few shots.

Since the lens must travel several centimetres to accommodate various wavelength focusing, a precision drive mechanism capable of moving this massive optic against atmospheric pressure has been designed and prototypes have been fabricated and tested. A photograph of the lens drive mechanism in partial assembly is shown in Fig. 16.

TARGET CHAMBER

Figure 17 is an artist's conception of the Nova target chamber. The five (west) beams are equally spaced in angle upon the surface of a cone whose vertex is at the target. These beams are mirrored by the east beams, so that east and west beams do not radiate into each other through a coordinate system centered at the target. The cone angle itself can be varied (from 80 to 100 deg) to provide flexibility in dealing with various experimental target designs. Figure 17 also shows some of the ancillary target event diagnostic systems. This configuration will allow for a full complement of experimental and diagnostic instruments. The five-beam overlap spot in the common focus is not expected to exceed 250 μm in diameter, including allowances for alignment, positioning, and verification tolerances. This criterion applies for a nominal focal length of 3.0 m.

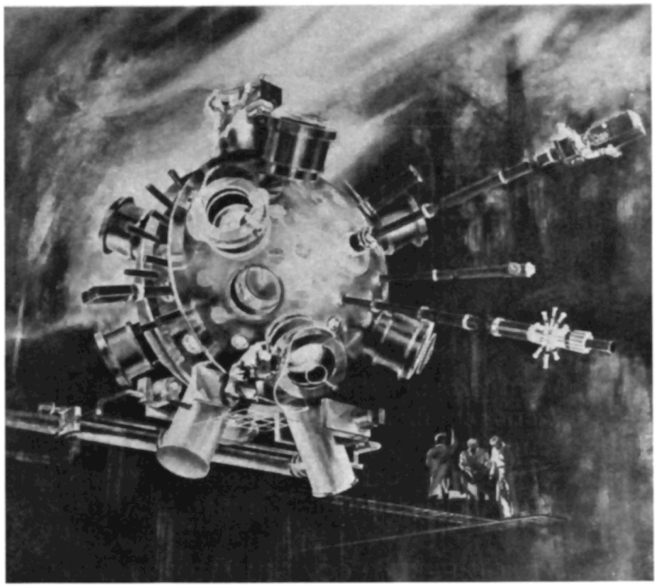

Fig. 17. Nova target chamber, showing ten laser beams on a 100-deg cone. Targets are positioned from a manipulator at the top of the chamber. Some of the target event diagnostics are also indicated in this artist's rendition.

The Nova target chamber[i] is shown in Fig. 18 as ready for installation. This 2.3-m-radius aluminum chamber features 5-in.-thick walls to accommodate component mounting without undue deflection, strain, and consequent component misalignment. Aluminum has been chosen because of its rapid recovery from radioactivity following a high-yield target shot.[25]

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[i] The Nova target chamber was built and tested by the Chicago Bridge and Iron Company, Memphis, Tennessee.

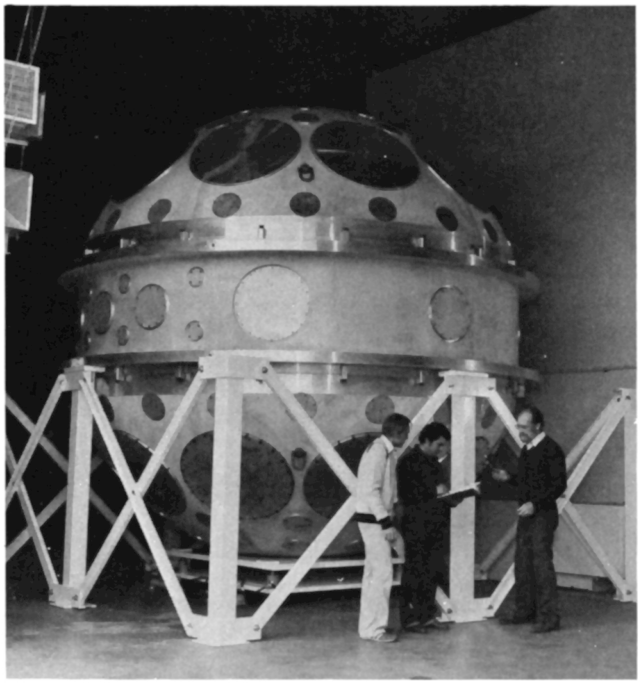

Fig. 18. Nova target chamber. The assembly is vacuum checked and ready for mounting on its spaceframe.

POWER SYSTEMS AND ENERGY STORAGE

The Nova power system[26] has been designed to meet several simultaneous goals: performance, cost, reliability, and noise reduction. The approach has been to improve on known performance from the Shiva system and to thoroughly test each design and component under actual operating conditions. Subsystems have met their individual requirements in various tests. Most parts for Nova have been delivered, and assembly has commenced. Fifty megajoules of stored energy are required in the 1600 high-power circuits, which drive 4400 flashlamps and 32 Faraday rotators. Fifteen to 20 MV·A of peak ac power is drawn from the 13.8-kV three-phase lines to charge the capacitance bank in 30 s. High-density capacitors comprising the bank are provided.[j] Seven 1.5-MV·A power supplies[k] do the majority of the charging; twenty-one 100-kV·A supplies do the rest. Switching is performed by 100 dual-ignitron switches. Control is provided by a computer hierarchy, with DEC LSI/11-23 front-end processors and DEC VAX computers for high-level command. Fiber optics is used throughout the control system to avoid electrical fault and noise propagation. All circuits are extensively monitored for waveform abnormalities that are indicative of faulty lamps. The goal is, of course, to detect and replace such lamps before they explode on a subsequent shot.

COMPUTER CONTROLS

Complex systems like Nova, requiring literally hundreds of electronic and electromechanical control functions for a single laser-target experiment, must rely on an extensive, sophisticated computer control network. The control system architecture is designed to handle multiple tasks (such as laser alignment, target alignment, capacitor-bank charge-and-fire sequencing, and laser and target diagnostic data processing) from a centralized location. Common hardware and software routines allow functional redundancy. For example, two (of the three) top level VAX-11/780 computers[l] are capable of operating the entire system through a task-sharing network and through extensive memory sharing. The Ramtek touch-panel display consoles are likewise functionally redundant and interchangeable.

Control and data acquisition functions are performed by a distributed, hierarchically organized network of computers and devices interconnected through high-speed fiber optic communications links. The architecture established for this control system provides the flexibility within each of its four fundamental subsystems to optimize internal design and organization according to their particular criteria. Control system integration, support of common functions, and centralization of operation are achieved using a fifth unifying subsystem called "central controls."

The Nova control system must satisfy control and data acquisition functions for four fundamental areas:

1. *Power Conditioning*. Capacitor bank activation, laser firing, and system timing
2. *Alignment*. Laser and target alignment
3. *Laser Diagnostics*. Measurement of beam energy and quality
4. *Target Diagnostics*. Measurement of target performance.

The control system has been organized into four fundamental subsystems corresponding to each of these areas, with a fifth unifying subsystem, central controls, responsible for integrating functions and centralizing operations. Over 5000 individual control

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[j] The capacitors are provided by Maxwell Laboratories, San Diego, California, and by General Electric Company, Valley Forge, Pennsylvania.

[k] Supplied under contract by Aydin Power Systems, Palo Alto, California.

[l] Supplied by Digital Equipment Corporation.

and data acquisition elements are supported. These include stepping motors, video images, calorimeters, high-voltage power supplies, interlocks, 20-kV digitizers, transient digitizers, and remote image memories.

Control system requirements for these elements range from simple status monitoring of switch closures to the substantial demands of closed loop alignment through the image processing of two-dimensional beam profiles.

The hardware architecture of the Nova control system is illustrated in Fig. 19. The fundamental "building block" for local control and data acquisition functions is the LSI-11/23 microcomputer. The LSI-11s are packaged in an LLNL-designed chassis that provides power and input/output space for large configurations. These microcomputers are set up with memory, local control panels, device interfaces, and software specifically matched to their individual functions. Typical applications of these units include firing power-conditioning ignitrons, configuration control of the Nova output sensors through stepping motor manipulations, and acquisition of data from beam and target system calorimeters.

Real-time control of laser operations is performed by the power-conditioning control system, which synchronizes all active laser components (amplifiers, isolators, shutters) with the master oscillator/pulse-generator, monitors laser systems during the firing sequence, and controls and monitors pulsed power segments of the laser system. Communication with active devices and components is accomplished through an extended computer bus. The control system computer bus network is called "NOVABUS" and is implemented using fiber optic cables. The NOVABUS design features global synchronization bits, and it is accurate to 1 μs. Synchronization of devices requiring submicrosecond timing is accomplished using triggers from the master oscillator electronics. This subsystem is hardwired and employs very broad bandwidth circuitry, enabling electronic and optical pulse synchronization to <1 ns in critical timing applications.

One example of the alignment system's remote, closed-loop alignment capability is its ability to automatically position each of the 140-odd spatial filter pinholes scattered throughout the laser bay. An alignment beam is detected with a charge-coupled device (CCD) array (the solid-state equivalent of

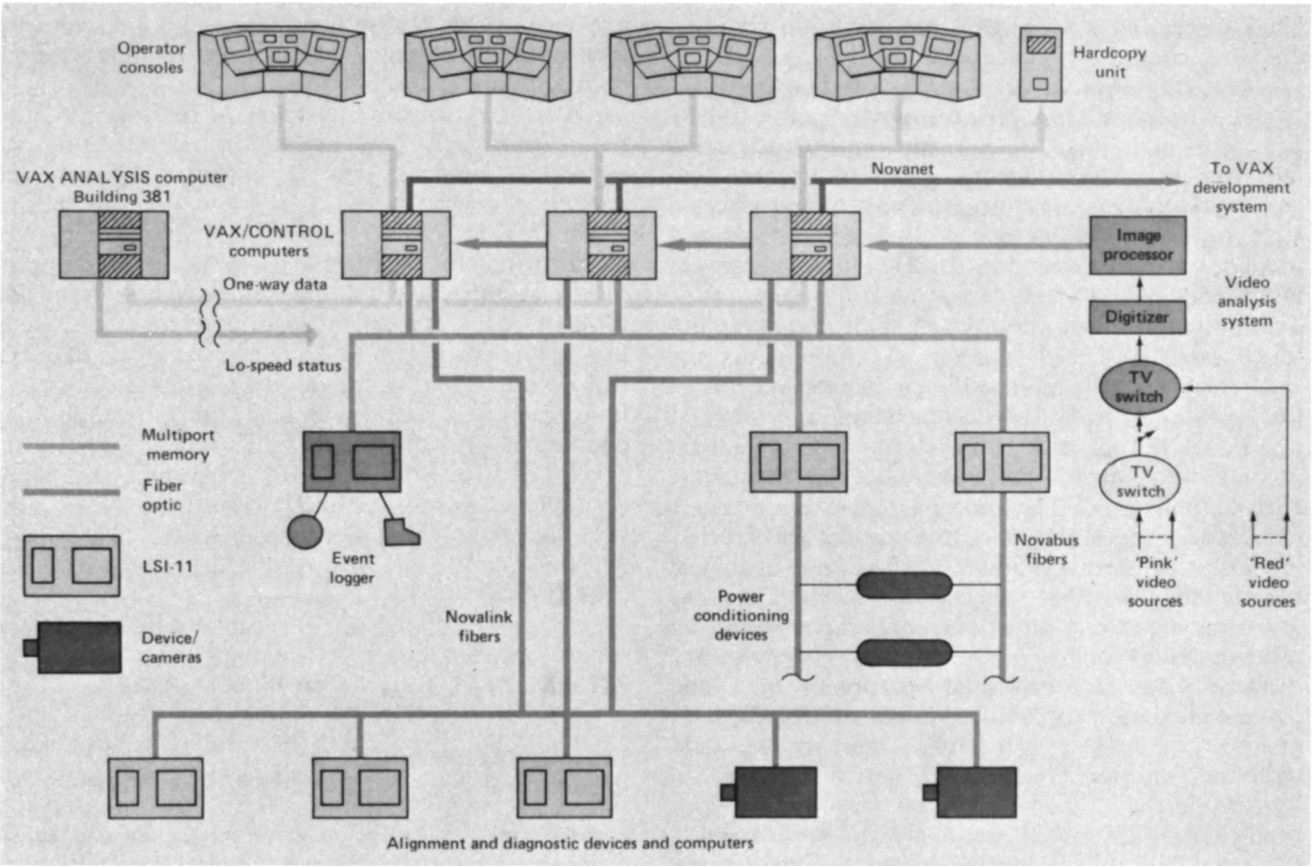

Fig. 19. Schematic of Nova control system architecture.

a television vidicon camera) located in the output sensor package (Fig. 2). This array represents the state of the art in image sensors and offers greater than a factor of 10 improvement over conventional vidicons in dynamic range. The sensor-package optics image the plane of the pinhole on the CCD array. The image is automatically processed by the control system, which then commands stepper motors to position the pinhole to a preset location (as judged by the pinhole image location on the CCD). The alignment control subsystem is capable of aligning all of the Nova pinholes within 30 min.

The control system also communicates with many distributed devices through an extensive fiber optic network, featuring high data transfer rates (10 Mbit/s), low overhead through direct access to computer memory, and programmable network connections. To facilitate block data transfer, which is especially useful for image data processing, the sophisticated NOVANET interconnection system has been implemented using intelligent "Novalink" controllers, which can communicate both to remote LSI-11/23 computers and to remote memories of stored video images. NOVANET is a high-speed, bit-serial, fiber optic, distributed communication network used on the Nova laser alignment and diagnostic computer control system. NOVANET provides multidrop capability between computers and remote interface devices, error detection on each data transfer, and low computer system overhead. NOVANET is used on our distributed control system, which includes three VAX 11/780 computers, ~50 LSI-11 processors, and 15 CCD television cameras. All transfers over NOVANET, including the transfer of digitized video information, utilize direct memory access techniques. The Nova target data acquisition and vacuum control system uses CAMAC instrumentation interfaces and LSI-11/23 acquisition processors. This system is menu controlled with color-graphics touch panels. A wide variety of components are controlled, ranging from vacuum pumps and valves to 10-ps resolution CCD streak cameras.

NOVANET physical connections to hardware are accomplished via a "star" configuration through a central "node star." The node star serves as a repeater for all incoming messages, retransmitting to all other processor or device "nodes." Therefore, a logical bus topology is created by the use of the node star since any node can directly communicate with any other node.

Another commonly used feature is the node star segmentation capability. Segmentation isolates a group of nodes performing large volume data transfers from the rest of the network. Thus, by segmenting the node star into two parts, the network bandwidth is effectively doubled. The node star has the capability of segmenting into 64 separate subnetworks. Once the large volume data are transferred (for example, moving a digitized video image from a remote camera to the control room VAX), the processor controlling the node star reconnects the segments to allow normal communication between all nodes.

The target diagnostics system has the task of recording a wide variety of signals from many diagnostics instruments surrounding the target. These instruments include x-ray and particle detectors, calorimeters, and other instruments to diagnose target shot results. Detectors in these instruments range from CCD streak cameras with 10-ps response, photomultipliers and silicon photodiodes with 1- to 2-ns response, to light and particle calorimeters with response times measured in seconds. This wide range of bandwidths and wide variation in signal levels means that close attention must be given to diagnostic isolation and grounding to prevent cross-talk and signal degradation.

The system is LSI-11 and CAMAC based. It utilizes geographically distributed LSI-11 processors to control various analog-to-digital converters placed near the analog signal source. This minimizes analog signal cable lengths while maximizing the signal-to-noise ratio. All diagnostics are isolated from the target chamber, the spaceframe, and multiple building grounds. Each diagnostic area is isolated by using fiber optics for all inputs and outputs, with the one exception being the ac lines. These are isolated using low-capacitance power transformers and a single point grounding scheme.

A major software development in Nova has been the design and implementation of the PRAXIS high-level programming language. PRAXIS was conceived originally as "COL" by Bolt, Beranek & Newman, Inc. (BBN) in response to an early U.S. Department of Defense programming language specification, which led eventually to the definition of ADA. ADA is a long-term effort expected to yield full compilers in 1983. Languages such as PRAXIS and ADA have control-system-oriented features that increase the readability and corresponding maintainability of system software. PRAXIS was developed for Nova by BBN to provide the most desirable features of ADA within the Nova software development timeframe. Approximately 95% of Nova controls software is currently written in PRAXIS.

PRESENT STATUS OF NOVA CONSTRUCTION

The laboratory and office buildings were completed in June 1982. Installation of the tubular steel spaceframe supports for laser components, turning mirrors, output sensor packages, and target chamber is nearing completion, and installation of laser components will commence in April 1983. More than 60% of hardware procurements are currently under contract and in fabrication, and assembly of components is well under way. Construction of the power circuits is approximately at the 50% point. The target chamber has been fabricated, accepted as vacuum tight, and delivered. Other subsystems–alignment, laser diagnostics, and controls–are extensively deployed in support of Novette. This two-beam early version of Nova employs Nova hardware wherever possible; it is currently functioning as a prototype laser system, and performing selected advanced target experiments as well. The activation of Novette has proven to be an extremely valuable learning experience for the coming activation phase of Nova. We confidently expect that Nova will meet its cost, schedule, and performance goals.

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It is impossible in a project of this scope to recognize all of the contributors. The lead project engineers, however, deserve special recognition for their efforts and their professionalism: these are C. A. Hurley, mechanical systems; E. P. Wallerstein, optical components; Erlan Bliss, alignment systems; R. G. Ozarski, laser diagnostic systems; M. A. Summers, frequency conversion and target focusing systems; F. Rienecker, target systems; D. Kuizenga, oscillator and splitter systems; J. R. Severyn, target diagnostic systems; F. Holloway, controls; K. Whitham, power systems; and C. Benedix, conventional facilities manager. D. R. Speck will be in charge of Nova activation. No project succeeds without good management; the authors thank their able deputies, A. J. Levy and G. J. Suski. On behalf of the Nova project, the authors acknowledge the continuing support of J. L. Emmett and J. F. Holzrichter. Finally, the authors acknowledge with gratitude the enthusiastic, innovative, and dedicated efforts of American industry in support of this project; without their close collaboration, we would not be nearly as advanced.

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