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Engineering Design of the Nova Laser Facility for Inertial-Confinement Fusion

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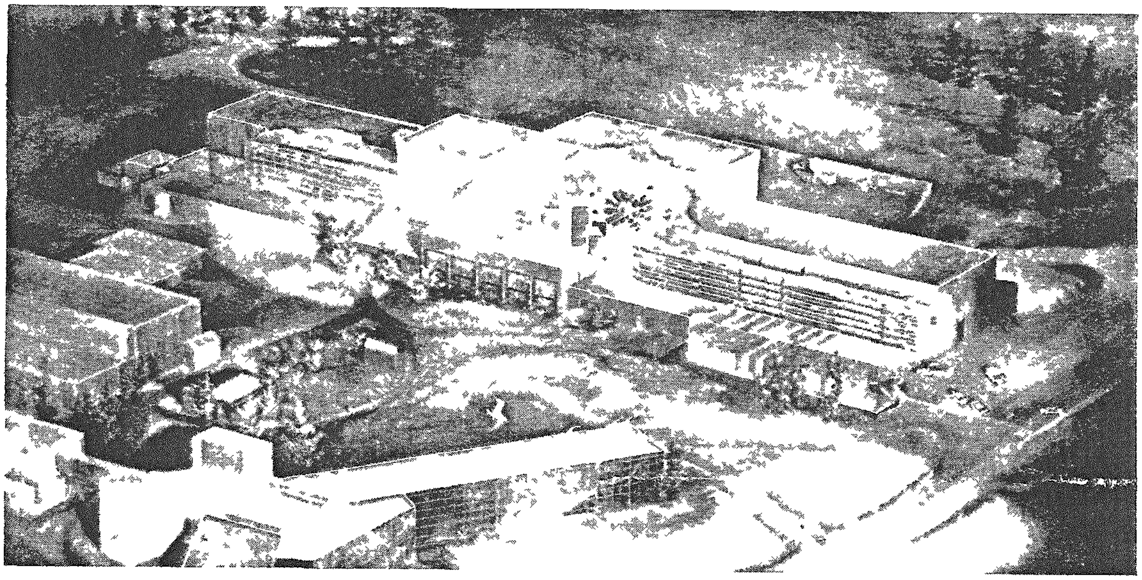

January 25, 1982

Lawrence Livermore National Laboratory

Work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

ENGINEERING DESIGN OF THE NOVA LASER FACILITY FOR INERTIAL-CONFINEMENT FUSION*

by

W. W. Simmons, R. O. Godwin, C. A. Hurley, E. P. Wallerstein, K. Whitham, J. E. Murray, E. S. Bliss, R. G. Ozarski. M. A. Summers, F. Rienecker, D. G. Gritton, F. W. Holloway, G. J. Suski, J. R. Severyn, and the Nova Engineering Team.

Abstract

The design of the Nova Laser Facility for inertial confinement fusion experiments at Lawrence Livermore National Laboratory is presented from an engineering perspective. Emphasis is placed upon design-to-performance requirements as they impact the various subsystems that comprise this complex experimental facility.

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Foreword

The Nova Laser System for Inertial Confinement Fusion studies at Lawrence Livermore National Laboratories represents a sophisticated engineering challenge to the national scientific and industrial community, embodying many disciplines - optical, mechanical, power and controls engineering for examples - employing state-of-the-art components and techniques. The papers collected here form a systematic, comprehensive presentation of the system engineering involved in the design, construction and operation of the Nova Facility, presently under construction at LLNL and scheduled for first operations in 1985. The 1st and 2nd Chapters present laser design and performance, as well as an introductory overview of the entire system; Chapters 3, 4 and 5 describe the major engineering subsystems; Chapters 6, 7, 8 and 9 document laser and target systems technology, including optical harmonic frequency conversion, its ramifications, and its impact upon other subsystems; and Chapters 10, 11, and 12 present an extensive discussion of our integrated approach to command, control and communications for the entire system. Figure 1 represents a block diagram of the various major subsystems, and illustrates their functional relationships to each other and to overall system operation.

It is undoubtedly difficult for the casual reader to acquire an appreciation for the scope, scale and complexity of the eventual working facility. For two examples: more than one hundred miles of high voltage cable connect the capacitive energy store to the 8800 - odd falshlamps mounted within the individual laser amplifiers, while more than one thousand stepper motors must be controlled and positioned to accurately point and center the laser's twenty beams precisely throughout each amplifier chain and onto the target. Although we at LLNL have been able to build upon successes with earlier lasers such as Argus and Shiva, the scale of Nova is truly unprecedented; many examples are given throughout this series of papers. Nova represents, by far, the largest precision optical instrument ever to be fabricated; more than one acre of surface area will be precisely figured to extreme smoothness (fractions of a wavelength of light in both transmission and reflection).

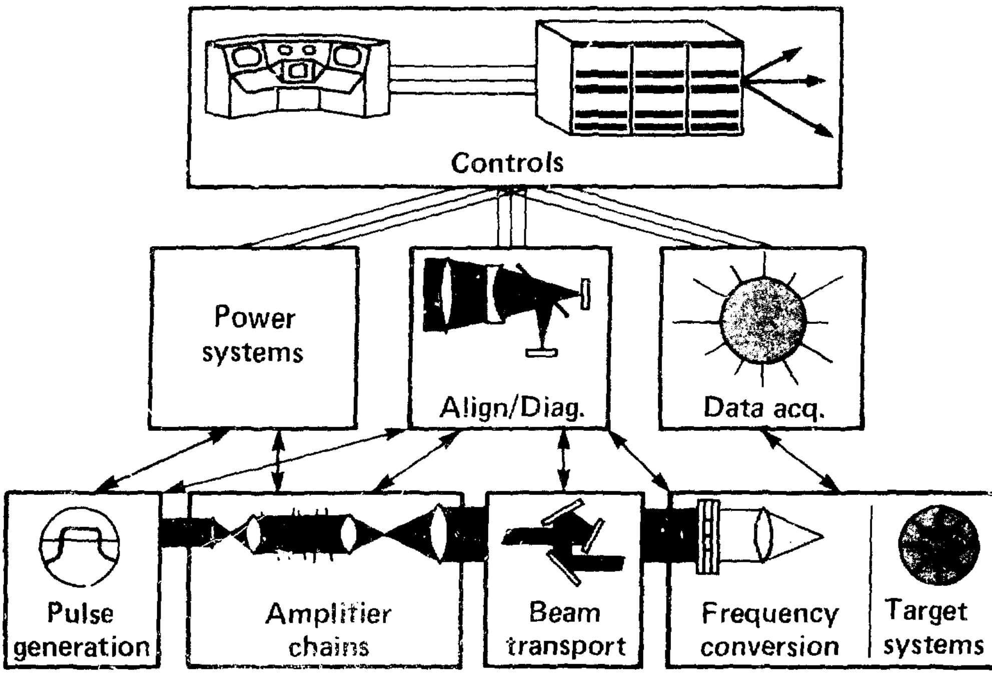
The Ninth Symposium on Engineering Problems of Fusion Research, held in Chicago, Illinois on October 26-29, 1981, provided a natural forum for this presentation set. The design engineering for Nova is virtually complete, and most of the hardware is currently in procurement. We therefore welcomed the opportunity for the comprehensive "design review" presented herein. I wish to thank Professor G. H. Miley, Symposium General Chairman: his capable staff: and the Symposium sponsors; the University of Illinois Fusion Studies Laboratories, the IEEE, the Department of Energy, the American Nuclear Society, Argonne National Laboratory, and EPRI for the motivation and opportunity to effect these presentations.

The Nova project has been advanced immensely by the cooperation of many industrial corporations throughout the country and the world. These corporations are our project partners, as dedicated as we at LLNL to the success of Nova and Inertial Confinement Fusion. At this (approximate) mid-point in the project, I take great pleasure in acknowledging the essential technological contributions of the following organizations:

A. C. Martin Associates
Aerojet General
Alliance Tool and Die
Aydin Power System
Bechtel Group, Inc.
Bendix Field Services
Allen Bradley, Ltd.
Carborundum
CTI Cryogenics
Chicago Bridge and Iron
Cleveland Crystals
Corning Glass
Design Optics
Digital Equipment Corp.
Eastman Kodak
E. G. & G., Inc.
Electronics Metal Finishing
Floating Point Systems
Gar Electroforming
General Electric
Helfrecht Machine Co.
Heraeus-Amersil
Hewlett-Packard
Hoya Glass Co.
ILC Technology
Interactive Radiation
Kaiser Engineering
Kigre Inc.
Klinger Scientific Corp.
Lasermetrics
Maxwell Laboratories
Meadville Precision
Optical Coating Laboratories
Perkin-Elmer Corp.
R.C.A.
Ramtek Corp.
Schott Optical Co.
Sheller-Globe Corp.
Spectra Physics
Stainless Equipment Co.
Tinsley Laboratories
Zygo Corp.

I would also like to acknowledge the dedicated efforts of Micki Camacho, who prepared this extensive manuscript.

The figure illustrates, in block form, the relationships between major Nova facility subsystems. Overviews of these subsystems, what they do and how they interrelate, will be presented in the remainder of this paper. An editorial comment: throughout the text, each presentation is treated as a separate chapter, for which full authorship is listed. These authors constitute the Nova design team. Figures, figure captions and references are self-contained, and therefore start anew with each chapter.



In this collection of papers, I have sought to present an integrated and reasonably complete picture of the subsystems comprising this very complex experimental laboratory. Let future experiments form the judgment basis for our success!

W. W. Simmons
January 25, 1982

NOVA LASER SYSTEM FOR INERTIAL CONFINEMENT FUSION

1. INTRODUCTION

Over the past several years, LLNL has built and operated a series of increasingly powerful and energetic laser systems to study the physics of inertial confinement fusion (ICF) targets and laser-plasma interactions. Nova, the latest in this series, is the successor to the Argus and Shiva lasers. The Nova 20 beam laser is capable of concentrating 200 to 300 kJ of energy (in 3 ns) and 200 to 300 TW of power (in 100 ps) on experimental targets. It will be housed partly within the existing Shiva building and partly within a new 10684-m^2 (115,000 ft^2) laboratory building adjacent to the existing Shiva facility (see Fig. 1). It is being constructed in two phases. The first 10 beams are in the new laboratory bulding. The second 10 beams will be in the Shiva Facility.

The Nova laser fusion research facility, currently under construction at LLNL, and authorized by Congress, will provide research scientists with powerful new tools for the study of nuclear weapons physics and inertial confinement fusion. Nova is a large, solid state laser, generating a fundamental wavelength of 1.0 μm, designed to deliver 200-300 kJ in a few nanoseconds to appropriate advanced inertially confined fusion targets containing deuterium and tritium. At these drive levels, we are confident that conditions of thermonuclear ignition can be reached; furthermore, with frequency conversion to shorter wavelengths (.5 μm and .35 μm), there is a chance for scientific breakeven (kinetic energy of the reaction particles exceeding incident laser energy on target). The Department of Energy (DOE) has now approved construction of ten Nova laser beams, the associated laboratory buildings, and the harmonic conversion apparatus. The remaining ten beams are presently under consideration.

The Nova laser consists of 20 large (74-cm diam) beams, focused, synchronized and aligned precisely so that their combined energy is brought to bear for a small fraction of a second on a single target. The ultimate goal of the LLNL inertial confinement fusion 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 inertial confinement fusion attractive for both military and civilian applications. By the mid to late 1980s, Nova should demonstrate that we can produce the extremes of heat and pressure required to achieve ignition of the thermonuclear fuel. Additional developments in the area of high-efficiency drivers and reactor systems may make inertial confinement fusion attractive for commercial power production.

2. LASER DESIGN AND PERFORMANCE

The Nova laser system has master-oscillator-power-amplifier (MOPA) architecture. As shown in Fig. 2, a laser pulse of requisite temporal shape is generated by the oscillator, preamplified, and split into 20 beams. After traversing an adjustable optical delay path (used to synchronize the arrival of the various beams at the target), the pulse enters the amplifier chain, where (1) disk amplifiers increase the pulse power and energy, (2) spatial filters maintain the spatial smoothness of the beam profile while expanding its diameter, and (3) isolators prevent the entire laser from breaking spontaneously into oscillations that could drain its stored energy and damage the target prematurely.

Fig. 1 - Artist's conception of the Nova laser fusion facility in a cutaway aeral view.

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 upon the Faraday effect, assure interchain isolation.

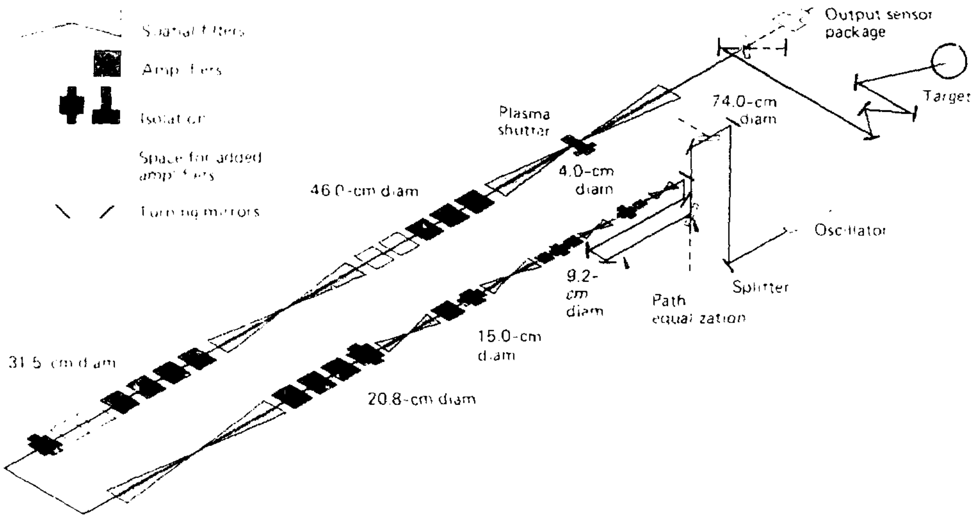


Fig. 2 - Schematic diagram illustrating the major optical components through which each (of 20) Nova laser beams will pass on its way from the oscillator (optical pulse generator) to the target.

Optimum spatial filter design provides entrance-lens to entrance-lens imaging. Thus, smooth beam intensity (through the cross-sectional area) is projected along the chain, and energy extraction by the laser pulse is maximized. Nearly all solid state laser systems now incorporate this multiple sequential spatial filter design approach.

When the pulse exits 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 approximately 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 it might damage or 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 component damage limit. The fluence (energy per unit area) at which optical components suffer damage exhibits a temporal dependence, as shown in Table I.

Table I

	Damage threshold, J/cm2		
	0.1 ns	1.0 ns	3.0 ns
Coated surfaces	2.5	8.0	8.5
Bare polished surfaces	6.0	19.0	33.0

It is apparent that uncoated surfaces will tolerate higher fluences than antireflection coated (AR-coated) surfaces. Thus, spatial filter input lenses, which are subject to the highest peak fluences, are left uncoated as the pulse passes through the various amplifier sections. The average fluence grows as a result of amplification of the pulse energy. However, the peak fluence grows faster because it is affected by both nonlinear self-focusing and diffraction from spatial noise sources. Beam expanding spatial filters reduce both the average fluence and the peak/average intensity ratio. Thus, the spatial filter output lenses and the target lens can be AR-coated.

Output power and energy performance for one Nova beam is summarized in Fig. 3. The upper curve represents hypothetical single-chain performance at the first-component-to damage limit if a perfectly smooth beam with a 70% filling factor 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/average ratio of the beam at the location of the threatened component. Computer estimates and operating experience with Shiva and Argus lasers lead to the lower curve, which represents an upper limit on performance of the laser at any pulse duration.

The full Nova complement of 20 beams will be brought to an integrated target chamber in two opposed clusters of 10 beams each. See Chapter 9 for a full discussion of the target chamber and its features.

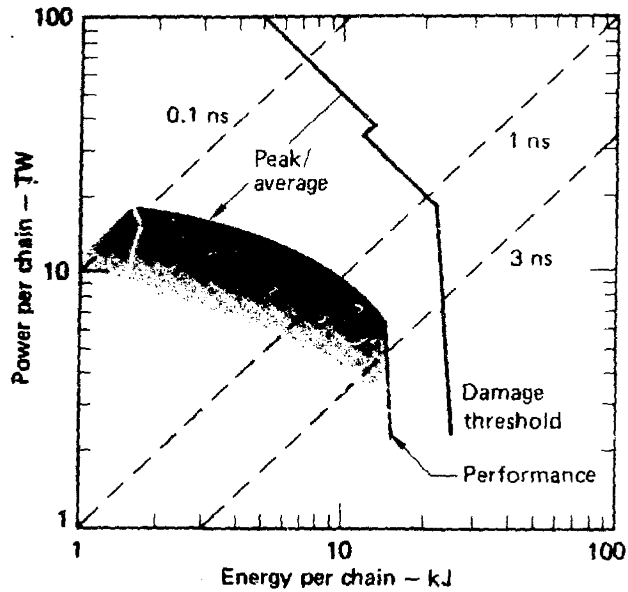


Fig. 3 - Performance limits, set by the threshold for beam damage to optical components, over the full temporal design range of Nova (0.1 to 3 ns). The operational regime is indicated by shading.

Figure 4 is an artist's conception of the Nova target chamber. The west beams are equally spaced in angle upon the surface of a 100° cone whose vertex is at the target. These beams are opposed by the east beams so that east and west beams can radiate into each other through a coordinate system centered at the target. Some of the ancillary target event diagnostics systems are also shown.

The line drawing in Fig. 4 illustrates design criteria for the overlap of Nova beams at a representative target. In the (common) focal plane, the beam overlap spot is not to exceed 150 m in diameter, including allowances for alignment, positioning, and verification tolerances. This criterion applies for a nominal focal length of 3.0 m.

Key Components

Disk amplifiers and other components with apertures of 21 cm or less are typical of Shiva based technology. The larger Nova amplifiers will feature a new rectangular internal geometry (as opposed to the current cylindrical geometry) that will permit flashlamps to pump the laser disks more efficiently. A side view of a partially assembled 46 cm rectangular amplifier is shown in Figure 5.

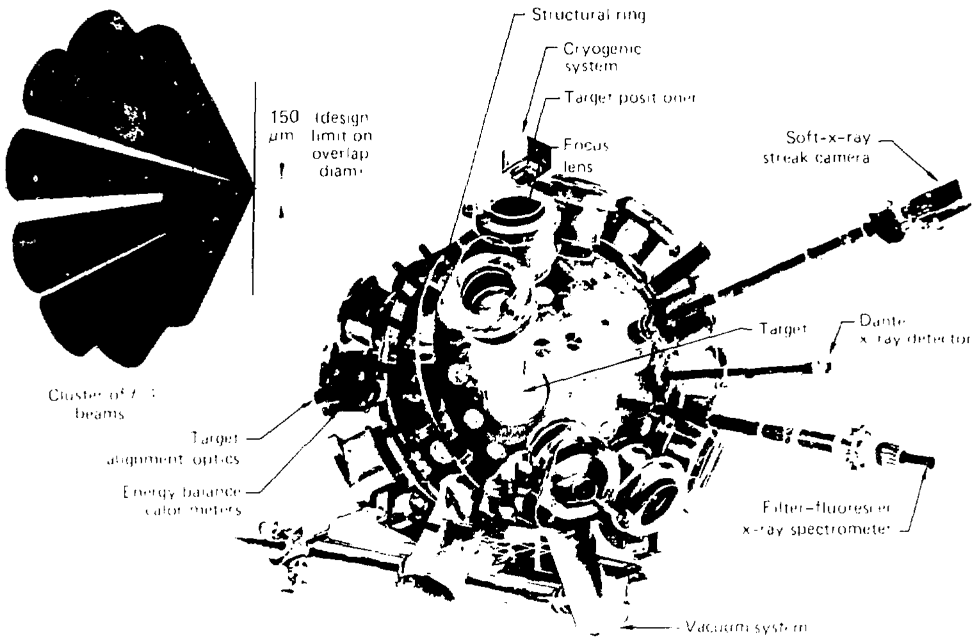


Fig. 4 - Artist's conception of the Nova target chamber, showing typical positions of some of the major experimental diagnostics. As shown in the insert (left), the beams in each of two opposed clusters are positioned on the surface of a 100° cone centered at the nominal target position.

Flashlamps run along two opposing sides of the rectangular case. Each flashlamp is backed by a silver-plated, crenulated reflector, which reflects light into the disk faces while minimizing absorption by neighboring flashlamps. Flat, silver-plated walls form the remaining two sides. The cavity is very reflective and provides tight optical coupling of light from flashlamps to disks. Careful design has produced significant efficiency improvements over prior amplifiers. We will employ rectangular disk amplifiers in the final three amplifier sections of Nova. Design criteria, most of which have been met in component tests, are summarized in Table 2.

Table II

	Amplifier aperture, cm		
	20.8	31.5	46
Glass type	Phosphate	Phosphate	Phosphate
Number of lamps/amplifier head	16	20	80 (transverse)
Number of disks/amplifier head	3	2	2 (split)
Stored energy (nominal), kJ	300	375	600
Small signal gain/head (nominal)	2.3	1.78	1.98

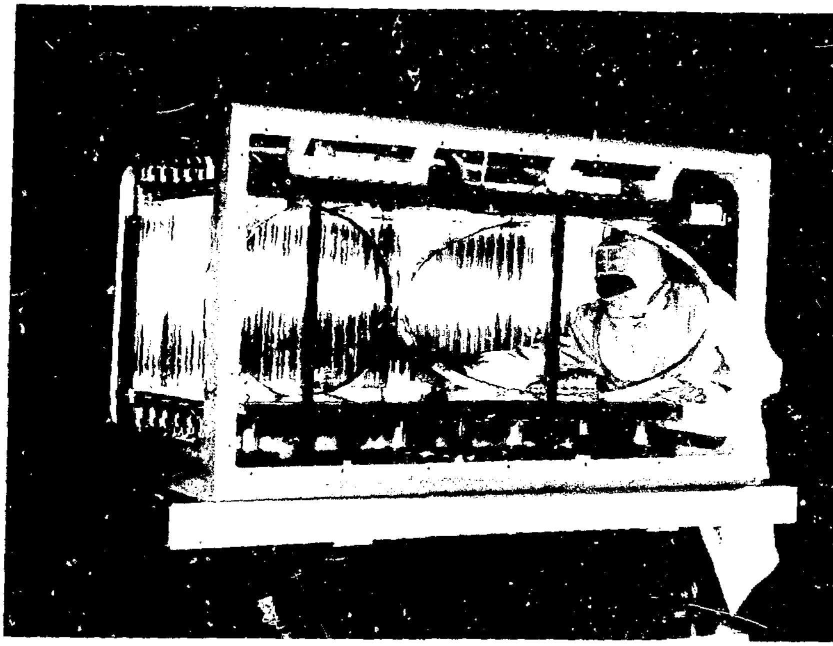


Fig. 5 - Partially assembled view of the 46-cm aperture rectangular laser disk amplifier. Half-disks are inserted in their elliptical holders. Transverse flashlamps and their reflectors appear at the rear of the amplifier. Interior metal parts are insulated to 50 kV to prevent arc-over. Most of the metal parts are electroformed nickel; Optical cavity interior parts are silver plated for high reflectivity.

Phosphate-based glass 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 large sizes to Nova specifications relating to optical quality and resistance to damage. We have, therefore, chosen phosphate to be the host material for the active Neodymium ions.

With disks of large diameter, the gain path for internally generated amplification of spontaneous emission (ASE) becomes longer. Internal ASE represents a parastic drain 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 why the disks are split along their minor diameters. Much higher energy storage and gain can be realized from a 46 cm diameter disk when it is split as shown in Fig. 5.

In order to protect the laser itself from light returning from the target, an absorbing plasma is injected into the final spatial filter near the location of its common focus. This 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. (Such light reappears at the plasma within about 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 that is created with an energy store of 6 kJ is sufficient to ensure closure. Instrumentation within the device senses malfunctions (for example, prefire) and, through the power controls system, prevents the laser pulse from arriving at this point, thus "aborting" the shot.

Further details of the laser components, in terms of their design criteria, design performance, and fabrication will be presented in several of the following chapters.

Subsystems

The capacitive energy store for Nova active components (flashlamps and Faraday rotators) exceeds 120 MJ. It is extensively instrumented to provide real time circuit component fault detection (there are more than 2800 flashlamp circuits). Information concerning the state of the electrical components, as well as charge and fire command controls, is transmitted between energy storage areas and central controls over an extended bus system based upon fiber optics circuits. Additional features of the power conditioning subsystem will be described in Chapters 5 and 10.

Complex systems like Nova, requiring literally thousands of electronic and electromechanical control functions for a single laser target experiment, must rely upon 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) VAX-11/780 computers are capable of operating the entire system through a task-sharing network. The same is true of the operator touch-panel display consoles, which are interchangeable.

The control system 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 through fiber optics communication channels. Extensive discussions of various aspects of the control system will be presented in Chapters 11 and 12.

The alignment/diagnostics subsystem ensures that the laser pulse will: (a) pass through all of the laser components without vignetting; (b) arrive at target at the proper time, with the proper energy/power characteristics, and in the multibeam geometrical configuration prescribed by the experiment; and (c) verify that these events have occurred during the post-shot analysis. Alignment of the laser system is planned to be automated, and achievable (from "warm" start) within 30 minutes. The subsystem relies heavily upon communications via Novanet with central controls, and features extensive deployment of image-processing CCD array cameras. This subsystem will be elaborated upon in Chapter 7.

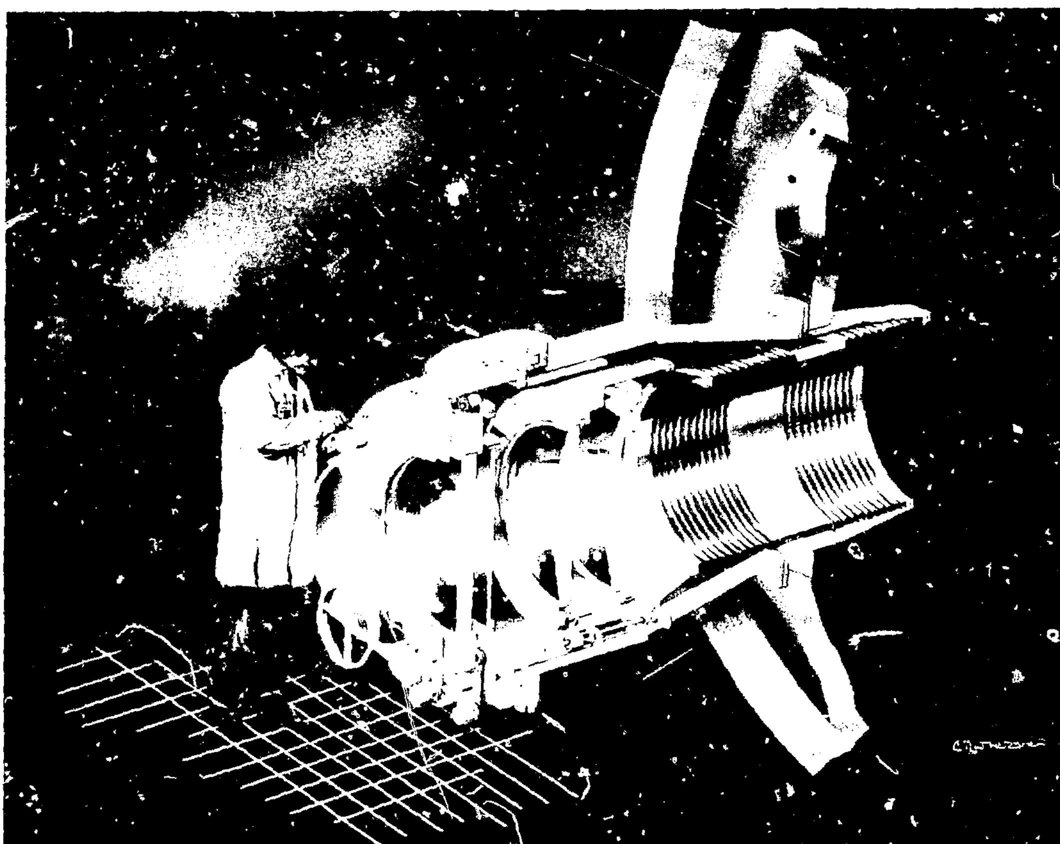


Fig. 6 - Artist's conception of the component arrangement comprising the frequency conversion array and doublet target focusing lenses. Beam aperture is 74 cm; doublet effective focal length is 3 meters.

Frequency Conversion

Target experiments with wavelengths shorter than 1.0 μm have validated significant improvements in light-plasma coupling physics. Experiments with smaller lasers have demonstrated the feasibility of frequency conversion, with Nova, to target irradiation light of wavelengths 0.525 μm and/or 0.35 μm, with little loss of focusable energy or power. Accordingly, we are proposing that Nova incorporate this capability within its mission guidelines. Frequency conversion can be accomplished by the deployment of arrays of potassium dihydrogen phosphate (KDP) crystals between the laser and the target. The concept is shown in Figure 6, and discussed in some detail in Chapter 8.

3. NOVA MECHANICAL SYSTEMS

In this chapter, the mechanical design features of large laser components, such as power amplifiers, spatial filters, Faraday rotators, turning mirrors, stable support systems and the integration of these components into the total system will be discussed.

Nova Laser Chain Components

Each laser chain is a series of amplifier stages, with a maximum amplifier output aperture of 46 cm. Spatial filters between the amplifier stages provide for filtering, relaying, and beam expanding. Faraday rotators, Pockels cells, and plasma shutters protect the optical surfaces from back reflections and subsequent damage. Each of these components will be discussed.

Amplifiers

There are three sizes of box amplifiers, namely, 20.8 cm, 31.5 cm, and 46 cm. There is also a 5 cm rod amplifier. A total of one hundred and ten (110) units are required for ten Nova beams. These units are all in fabrication.

Design of these amplifiers incorporates the latest innovations in amplifier technology. Figure 1 shows a cut-away rendering of the assembly of a 46 cm amplifier. This construction is typical of all sizes.

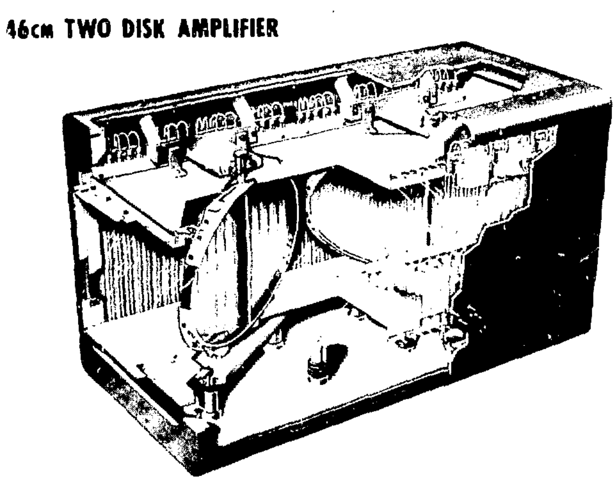


Fig. 1 - Two disk 46 cm amplifier with transverse flashlamps

We use a rectangular or box pumping arrangement, as compared to cylindrical geometry, in which the flashlamp light passes through the laser disks before striking other flashlamps; each large laser disk is split in half (only in the 46 cm) to reduce amplified spontaneous emission; and the disks are spring-mounted in electroformed elliptical holders held vertically in kinematic mounts. The pump cavity, totally enclosed by reflection surfaces, is designed for maximum reflectivity of the pump light (no gaps) and its volume is kept small for maximum pumping efficiency.

To reduce costs and improve quality, we have designed and built the disk holders and reflectors using an electroforming process of nickel, followed by silver-plating. Electroforming eliminates approximately 50% of the machining normally required.

Crenulated lamp reflectors can be seen behind the vertical array of flashlamps on either side of the laser disks. Top and bottom reflectors with recessed holes capture the disk holders. Quality control of the reflector silver plating is critical to successful operation of the pump cavity.

The 20.8 and 31.5 cm amplifiers have features similar to those of the 46 cm amplifier, except that the lamp orientation is longitudinal and the disks are not split.

This new design allows us to build very large amplifiers, simply and economically.

Spatial Filters

Seven spatial filters located between the amplifier stages in each laser chain control beam propagation by filtering, relaying, and expanding the beam. Figure 2 shows the size of the largest and last spatial filter in each chain. This filter expands the beam from 46 cm to 74 cm. Spatial filters consist of vacuum tubes sealed at both ends with lenses which focus the incoming beam on a pinhole and collimate the output beam.

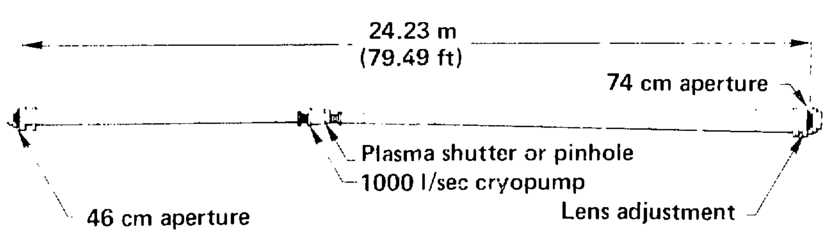


Fig. 2 - Spatial filter with 46 cm input aperture and 74 cm output aperture

Vacuum in the four largest filters will be maintained with 1000-l/s cryo pumps. The remaining units will be pumped with ion vacuum-pumping systems.

The spatial-filter lenses will be brought on the beam axis with adjusters capable of moving each lens in the x, y, and z directions under full vacuum. Vacuum integrity of the system will be maintained by stainless steel bellows.

Gear reducers on the largest spatial filter will be driven with stepping motors to automatically position the input and output lenses. A roller-bearing slide system will be driven through gear reducers to translate the spatial-filter lenses in the x-y plane.

Faraday Rotator Isolators

A Faraday rotator isolator is an electro-opto-mechanical device used to protect beam optics from back reflections and oscillations between the amplifier stages. It consists of an FR-5 terbium-doped rotator disk, a solenoid coil that surrounds the rotator, and polarizer plates (at each end of the coil) twisted about the optic axis by a relative 45° (see Fig. 3). When the coil is activated, it induces a magnetic field through the disk, which causes the polarization of a beam passing through the disk to be rotated in proportion to the strength of the field. This rotation, in conjunction with the appropriate relative orientation of the polarizer plates, allows for a 45° rotation and unattenuated transmission of the beam in one direction and a 45° rotation and deflection of a back-reflected beam. The deflected back beam is absorbed with a glass plate.

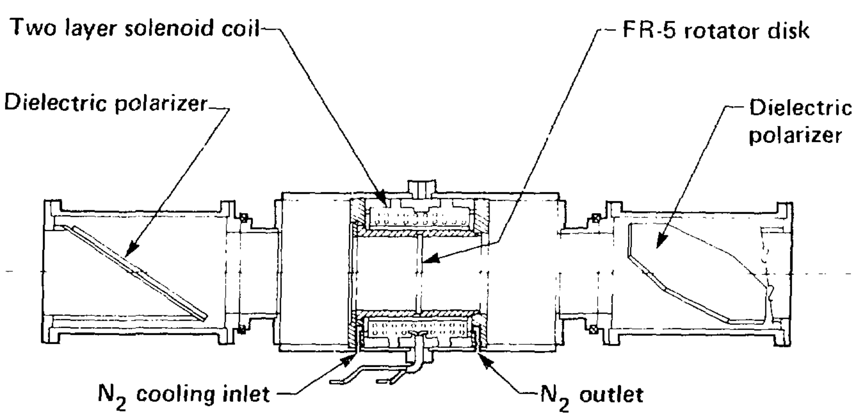


Fig. 3 - 31.5 cm Faraday rotator and polarizer assembly

The Nova system requires 42 Faraday rotators: two 5-cm and ten each of the 9.4-, 15-, 20.8-, and 31.5-cm clear aperture rotators. The mechanical design of these different sizes is the same and is scaled with respect to their apertures and the magnitude of the magnetic field of their coils.

In order to keep fringing fields exterior to the coil a minimum, the coil is surrounded with a cylindrically symmetric aluminum conducting shield. Because of its proximity to the magnetic field, however, this shield carries an energy penalty. To keep this penalty to a minimum and still have a workable design, we used shield-to-coil diameter ratios of approximately 2.

The rotator disk is mechanically separated from the coil to reduce the amount of mechanical shock transmitted to the glass when the coil is energized. Nitrogen gas flows between the coil and glass mounting to remove heat generated by the coil. The rotator components are attached through rubber dampening supports to the shield, which in turn is supported on cradles common to most components on the laser chain.

All components near the coil are made of either plastic or glass to avoid distortion of the magnetic field. The polarizer plates require a very accurately machined mount that is difficult to obtain with plastic; therefore, to minimize field distortion, we mount them on aluminum supports at a distance from the coil where the field is less than 400 gauss.

Using a single polarizer plate on each end causes an offset of the beam. Where it is affordable, namely the 5-, 10- and 15-cm sizes, two plates instead of a single plate are used at each location to take out the offset.

As beam size increases, Faraday rotator glass and energy storage become very expensive. An alternate, less expensive isolator, called a plasma shutter is used at the waist of the last spatial filter. It consists of a metallic foil closing an electric circuit. This circuit stands ready until the optical pulse has passed through the pinhole at which point electrical current sublimates the foil and creates a plasma jet across the beam path, blocking reflected light.

Mirror Assemblies

A total of 69 turning mirrors are used in the ten-beam system from the first beam aperture to the target. Mirrors range in size from 60.4 cm diameter and 111 lb. to 109 cm in diameter and 850 lb. Twenty mirrors must be mounted to allow transmission of 2% of the beam for diagnostics.

The mount design consists of an x-y adjustable mounting plate to which a mirror bezel is attached through three supports (see Fig. 4). Four different sized mounts, one of which uses two different bezel sizes, are required to accommodate five mirror sizes.

Three supports hold the bezel to the mounting plate attached to the bezel at three points 120° from each other. These supports are connected by a spherical rod end bearing at the bezel and hinges at the other end. All moving components are preloaded to prevent unwanted free movement of the mirror. One support is of fixed length, and the other two are adjustable to give the mirror angular adjustment about two mutually perpendicular axes. The adjustment is stepper-motor driven

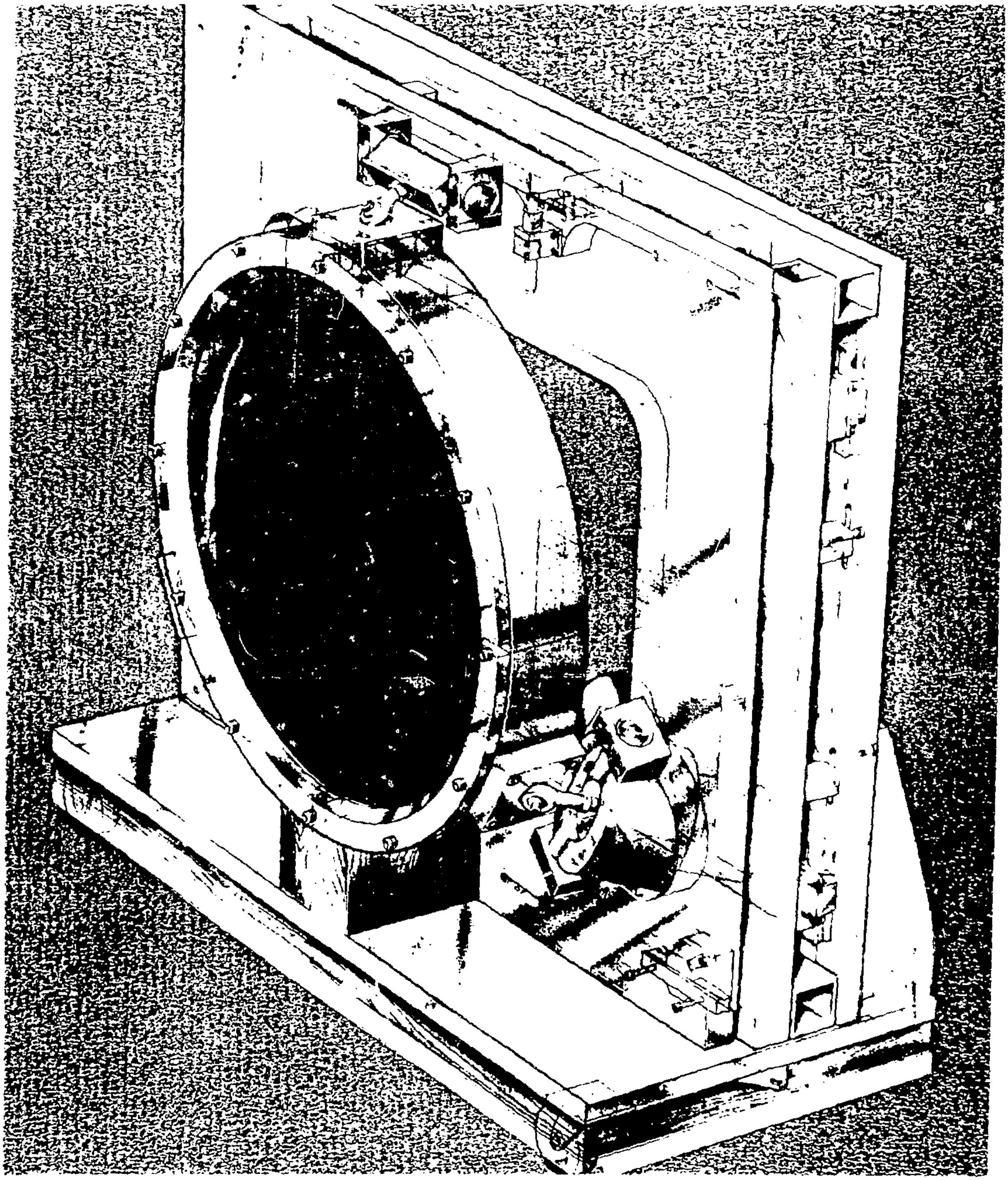


Fig. 4 - Mirror gimbal for 109 cm diameter mirror

through actuators which provide an overall resolution of .50 μrad/step through a total range in excess of 50 mrad.

The mirror is supported in a high-strength steel bezel that has an open back to reduce weight and allow transmission of the beam.

Mounting-plate x-y adjustment of ± 4 cm is achieved by using two plates, attached through linear bearings to a box frame between them. The mirror mounts to one plate, and the other plate mounts to the spaceframe. Adjustments are made through ball screws.

Component Assembly Facilities

The sensitive nature of huge optical systems requires that particulate contamination be minimized. Particles on optical surfaces result in surface damage when exposed to flashlamp or laser light. Laser components, the handling equipment, and the system, must be designed so that everything is reliably cleanable and easily maintained.

Because large components such as the turning mirrors require this special attention the entire machine is in a class 10,000 clean room. In addition, we have an assembly clean room, class 100, which is used for assembling the most sensitive components.

The class 100 clean room shown in Figure 5 will be utilized primarily for assembling amplifiers. We are modifying the clean room and designing new fixtures to handle, clean, assemble, and transport these large components.

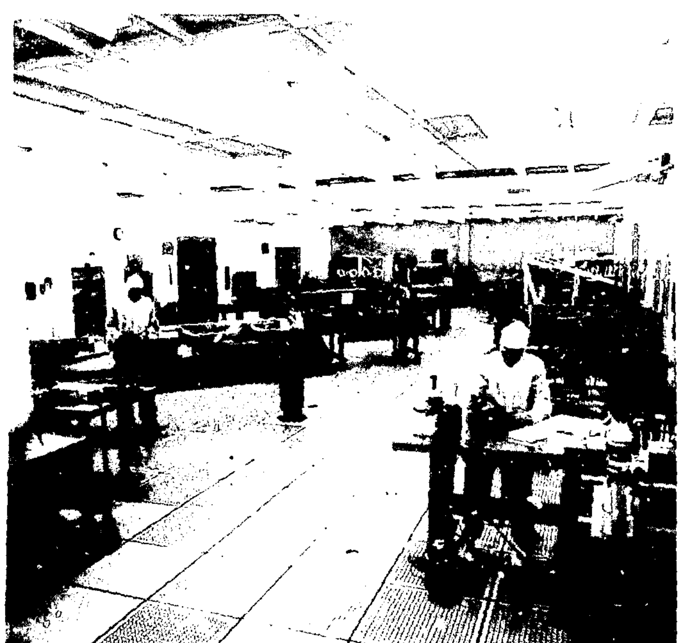


Fig. 5 - Class 100 assembly clean room

The clean room has a vertical air flow with an air velocity of about 30 m/min. High-efficiency particulate air filters are mounted overhead. Initially, a total of 305 Nova amplifiers will be processed; then the clean room will be used for continuous operational maintenance.

The room assembly stations consist of specially designed equipment for the sensitive assembly of optical components. It also has test stations for flashlamps and interferometry for testing optical mounting.

Carts are used to readily transport the box amplifiers to these various cleaning, assembly, and checkout stations.

High-pressure Freon spray booths are used for cleaning all metal parts. They have an internal rail system for transferring the box amplifiers from the transport carts into the booth. Here the housing and other amplifier parts will be sprayed clean, removing all particulate contamination. In seconds, the liquid Freon spray (at 1000 psi) will typically remove about 99.9% of particles 5 μm or larger. (Fig. 6) Laser disks are held in fixtures, washed and spin-dried, then assembled.

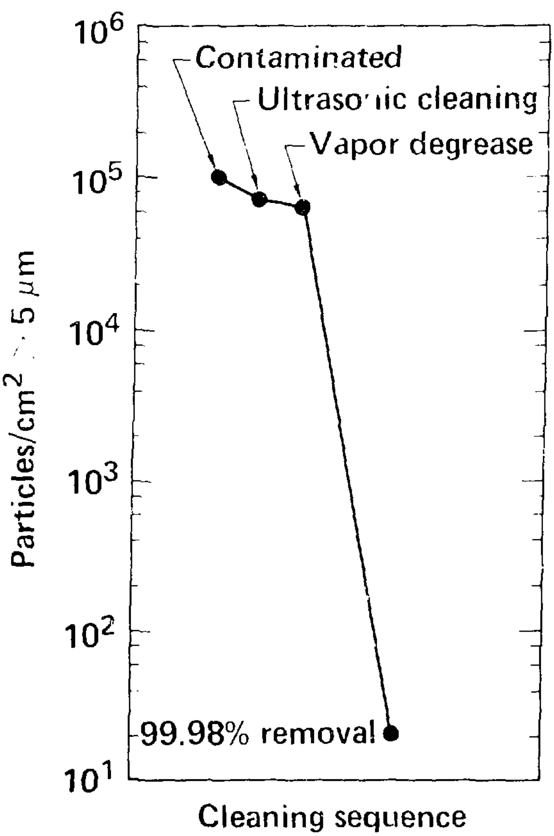


Fig. 6 - Efficient use of high pressure solvent spray to clean metal parts.

Spaceframes

Spaceframes serve as stable supports for all components in the laser system. Figure 7 shows the locations and relative sizes of the principal spaceframe structures. Optical components in the master oscillator room, located in the basement, are supported on a single table-high frame. Each of the frames located in the east and west laser bays support the larger optical components, providing a maximum of twenty amplified laser beams to the switchyard. Individual frames in the switchyard support either turning mirrors or beam diagnostic equipment. The remaining frame, located in the target room, supports the target chamber and additional turning mirrors which direct the laser beams coming from the switchyard onto the target chamber.

All frames are constructed using 6-inch-square tubing for main column and beam members; however, diagonal bracing members are constructed of 4-inch-square tubing for ease of fabrication. The frames are tied to the building with strategically located seismic anchors and allowed to thermally expand from the anchor locations on roller-bearing supports.

All frames are designed to be dynamically stable while accommodating convenient maintenance and utility access to components. To accomplish stability, computer analyses were used to establish the dynamic response of each frame to ground vibrations measured at the Nova site and to LLNL-design-basis seismic loadings. Deformations resulting from ground vibrations were judged to be acceptable on the basis of laser beam deflection; Table 1 itemizes the maximum translations and rotations calculated for each final frame design and the first three model frequencies calculated for each final frame design used in this assessment. Prerequisite model analyses of the frames were used to determine the influence of frame member size and locations, as well as variations in support and anchor restraint conditions.

The detail design of each frame, which was based on the requirements of the laser system it supported, is described under the appropriate headings below:

Master Oscillator Room Frame

The master oscillator support frame consists of accessible table-height "islands" which are tied together structurally below a raised floor. The "islands" stand above the floor supporting hardware on surfaces that are sandwich construction of plate steel and a commercial honeycomb table top. A seismic anchor is located near the middle of the frame and roller-bearing supports are located on the periphery of the frame base.

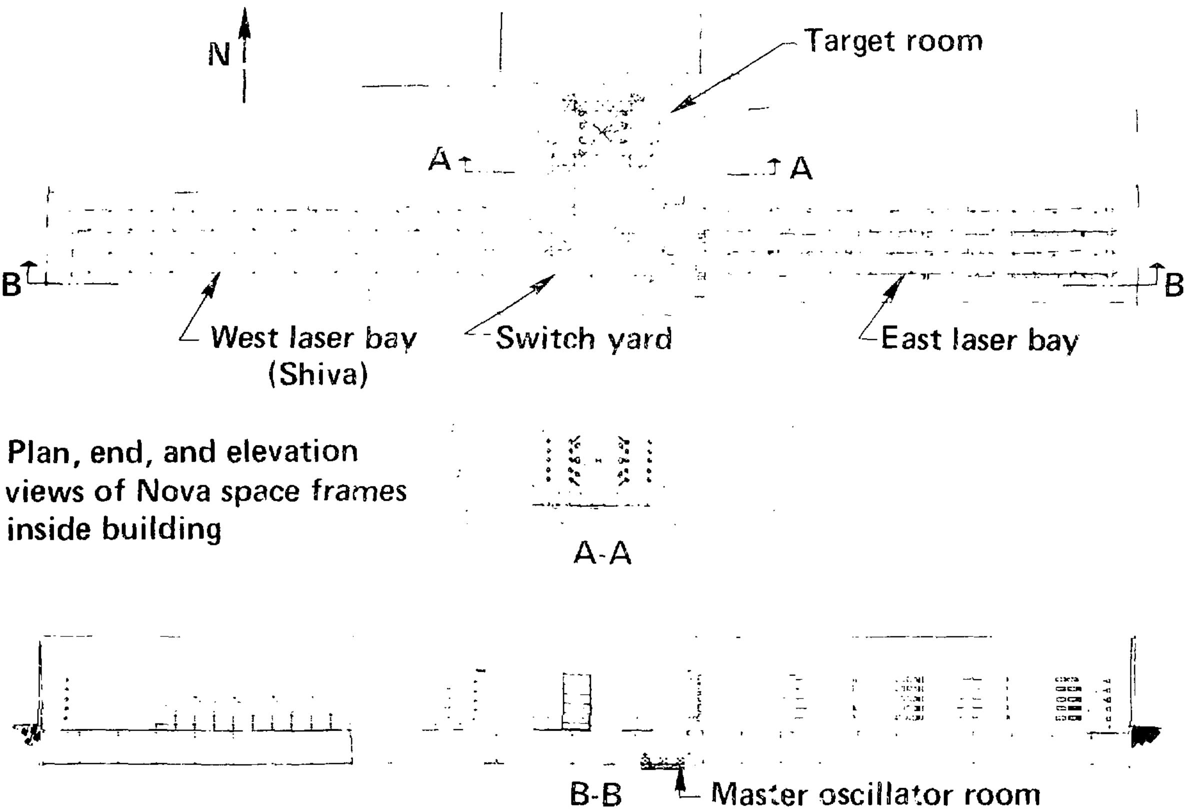


Fig. 7 - Overall arrangement of Nova showing spaceframe structure

Laser Bay Frame

Each laser bay frame is 192 ft long, 27.5 ft high and 10 ft wide. Diagonal bracing is provided at the mid-height along the length of both sides to give the frame longitudinal stability. For lateral stability, diagonal bracing is provided in the lateral plane at 20-ft intervals along the length of the frame. Additonal in-plane diagonal bracing is provided at three levels. Two seismic anchors are located near the center of the frame and linear bearing supports are spaced at 20-ft intervals along the frame.

Switchyard Frame

The mirror-support and diagnostic-equipment support frames are designed to be used in either a 10-beam or 20-beam laser system, with different orientations for each system. All frames are seismically anchored to the floor at multiple support points, since thermal expansion is not a major concern with small frame sizes.

These frames are dynamically stable, with rotation of the turning mirrors being of particular importance. The maximum anticipated mirror rotation is 0.4 rad with the deformations given in Table 1; the resulting deflection of the laser beams is acceptable as mentioned above.

Target Chamber Frame

The target chamber frame consists of a large upper structure, locating and supporting the target chamber and mirrors, and a beam-grid base structure. The overall height of the frame is 62 ft and covers a floor area of 71 ft by 47 ft. The base structure is laterally-supported by securing it to the building walls and vertically-supported by diagonally-braced columns. The upper structure is anchored to the base structure at four points below the centrally-located target chamber, and is allowed to thermally expand from these points on roller-bearings located between the upper structure and base structure. Lateral stability of the upper structure is provided by diagonal bracing and the overall geometric shape of the frame on the east and west ends of the frame.

Table I

Dynamic response of spaceframes due to ground vibrations.

Frame Location	First mode Hz	Second mode Hz	Third mode Hz	Translation μm	Rotation μrad
Master oscillator room	19.40	24.80	30.30	± 0.24	± 0.15
Laser bay	6.90	7.02	7.26	± 4.48	± 0.69
Switchyard					
Mirror	6.79	7.28	7.74	± 4.31	± 0.70
Diagnostic[1]	—	—	—	—	—
Target chamber[1,2]	3.16	3.99	4.81	± 2.82	± 0.36

1. Analysis of final design in progress
2. Model frequencies were evaluated for preliminary design

4. OPTICAL COMPONENTS FOR THE NOVA LASER

In addition to its other characteristics, the Nova Laser Fusion facility may well be the largest precision optical project ever undertaken. Moreover, during the course of construction, concurrent research and development has been successfully conducted, and has resulted in significant advances in various technical areas, including manufacturing efficiency. Although assembly of the first two beams of Nova is just commencing, the optical production, including construction of the special facilities required for many of the components, has been underway for over three years, and many phases of the optical manufacturing program for the first 10 beams will be completed within the next two years. On the other hand, new requirements for second and third harmonic generation have created the need to initiate new research and development. This work has been accomplished througn the enormous cooperation DOE/LLNL has received from commercial industry on this project. In many cases, industry, where much of the optical component research and development and virtually all of the manufacturing is being done, has made substantial investment of its own funds in facilities, equipment, and research and development, in addition to those supplied by DOE/LLNL.

Some statistics illustrating the massiveness of the project are as follows:

OPTICS FOR THE NOVA LASER (20 BEAMS)

2000 major optical components
4000 liters of laser glass
2000 liters of fused silica
20,000 liters of borosilicate glass
300 liters of crystals
400 m^2 of optical quality surfaces
200 m^2 of optical thin film coating
1.1 meter maximum diameter
380 Kg maximum weight
3 x 10^9 W/cm^2 at 1 nsec average fluence
0.06 micron average optical surface accuracy

In terms of optical components, for example, the 20 beam laser contains 98 mirrors between 0.8 and 1.1 m diameter with front surface accuracies of better than $\lambda/12$ at 633 nm wavelength. (This is flatness to within 2 microinches).

Basically the technologies for the Nova Optics divide into 1) material, 2) optical surfacing and figuring, and 3) coating, including thin film evaporated coating and newly developed techniques for producing integral anti-reflection coatings.

The optical technologies involved are shown in the following chart:

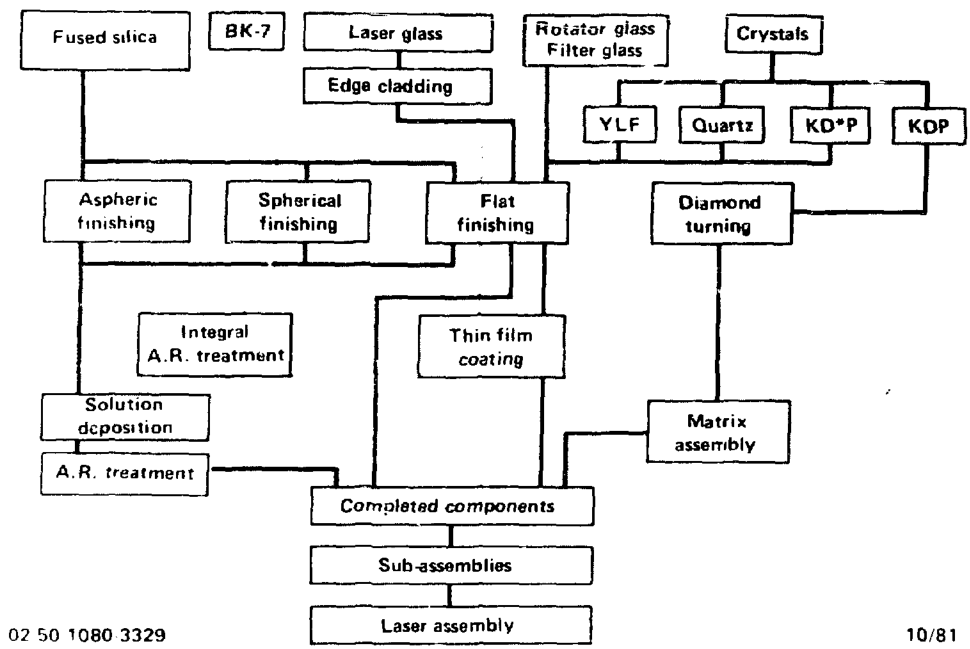


Fig. 1 - *Technology flow used for Nova Optics*

Advances in Material Technology

Many of the major challenges and achievements in the materials area have been the scale-up of previous technologies, in some cases by as much as an order of magnitude; in other instances, essentially new technology is involved.

Phosphate laser glass of the type being used for Nova was developed for, and has been used in recent years by; the University of Rochester, Osaka University and others, but with the largest disks about 2 liters in volume and surface dimensions of approximately 20 x 40 cm; most of the laser glass in Nova, however, resides in disks about 30 x 60 cm, having volumes on the order of 8 liters, which must be manufactured to the same precision specifications. The disks also require edge cladding to avoid spontaneous depumping by parasitic modes. The glass companies have developed highly damage resistant monolithic claddings. After the laser glass is poured and cooled in an initial annealing process, the glass is selected and ground to nearly its final shape. Then, an absorbing cladding is poured around the edge of the disks and the composite structure is then fine annealed. Basically the cladding is laser glass which has been copper-doped to strongly absorb the 1053 nm radiation. The doped material composition has to be adjusted so that it precisely matches two of the characteristics of the undoped glass: index of refraction, to avoid reflection at the glass/cladding surface; and coefficient of thermal expansion over the full temperature range required by the annealing process, to avoid residual stress in the glass, making it unacceptable for use in the laser. These large disks, when finished, require an optical homogeneity within $\lambda/6$ at 633 nm wavelength and a stress birefringence within 0.5 nm per cm. Hoya Optics U.S.A., in Fremont, California and Schott Optical Glass in Duryea, Pennsylanvia are the major manufacturers for the laser glass for Nova. (Kigre Corporation, Toledo, Ohio will also be manufacturing some of the smaller disks).

Advances made in recent years by Schott Optical Glass in the manufacturing of massive melts of boro-silicate glass (BK-7) have played a significant role in making Nova a cost-effective laser. As mentioned above, there are 98 massive mirrors in the system, some of which are required to have very high homogeneity because of transmission requirements for diagnostics. In addition, there are BK-7 lenses on every chain having a clear aperture of 77 cm: the output spatial filter lens and the diagnostic objective. The BK-7 glass for the first 10 beams is all poured and many of the components are complete. This material came from one large continuous melt. Fig. 2 taken at Schott in Duryea, Pennsylvania shows several of the large mirror blanks in their pre-finished stage.

One of the more remarkable recent achievements has been the size scale-up of solution grown crystal KDP (Potasium Dihydrogen Phosphate). Up to about 7 years ago the biggest crystals of KDP and KD*P (which is a somewhat slower growing deuterated form) were about 2.5 cm in diameter. For the Shiva laser, LLNL required the development of 5 cm KD*P for Pockels cells (and later began the development of 10 cm material for the same purpose). Subsequently the frequency conversion requirements arose and we began to work with the manufacturers to increase crystal boule size and to determine optimum potential sizes for crystal arrays for the 74 cm output apertures of the laser. It was decided to begin with 15-cm square crystals in a 5 x 5 array for the first 1 or 2 beams and to proceed from there with 3 x 3 arrays using 27-cm crystals. We have received and are currently finishing the first set of 15-cm crystals; and the first boule large enough to obtain 27-cm crystals has just been harvested.

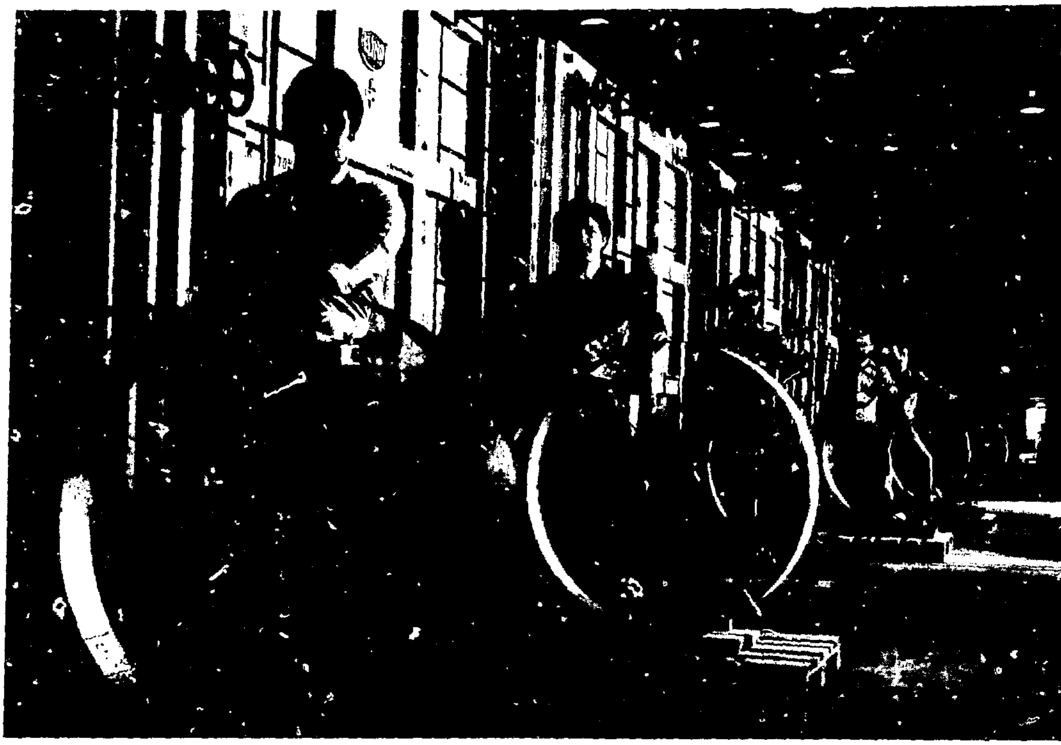


Fig. 2 - Borosilicate glass blanks for Nova Turn Mirrors, Schott Optical

The companies working on KDP crystal growth for Nova are: Cleveland Crystals, Inc., in Cleveland, Ohio, Interactive Radiation, in Northvale, New Jersey, and Lasermetrics, Englewood, New Jersey. Because the current manufacturing techniques grow crystals very slowly (roughly 1 mm/day), which is both a risk and cost liability. LLNL, in conjunction with North American Philips Laboratories, Briar Cliff Manor, New York, is developing another growth technique which has the potential of increasing the crystal growth rate by a factor of 2 to 4. The current technique depends on maintaining a saturated solution by very slowly dropping the temperature over an extended period of time. The alternative technique keeps recharging the growth solution which is held at a constant temperature. Our plan is to integrate this new technology into the Nova KDP production program as soon as the feasibility is demonstrated for large homogeneous crystals.

Fig. 3 is a picture of a recently harvested boule at Cleveland Crystals; next to it is the largest crystal made prior to LLNL's interest in the material. Fig. 4 is an interferogram made through one of Cleveland's 15-cm aperture crystals.

Fig. 3 - First boule of 27-cm KDP for Nova, Cleveland Crystals.

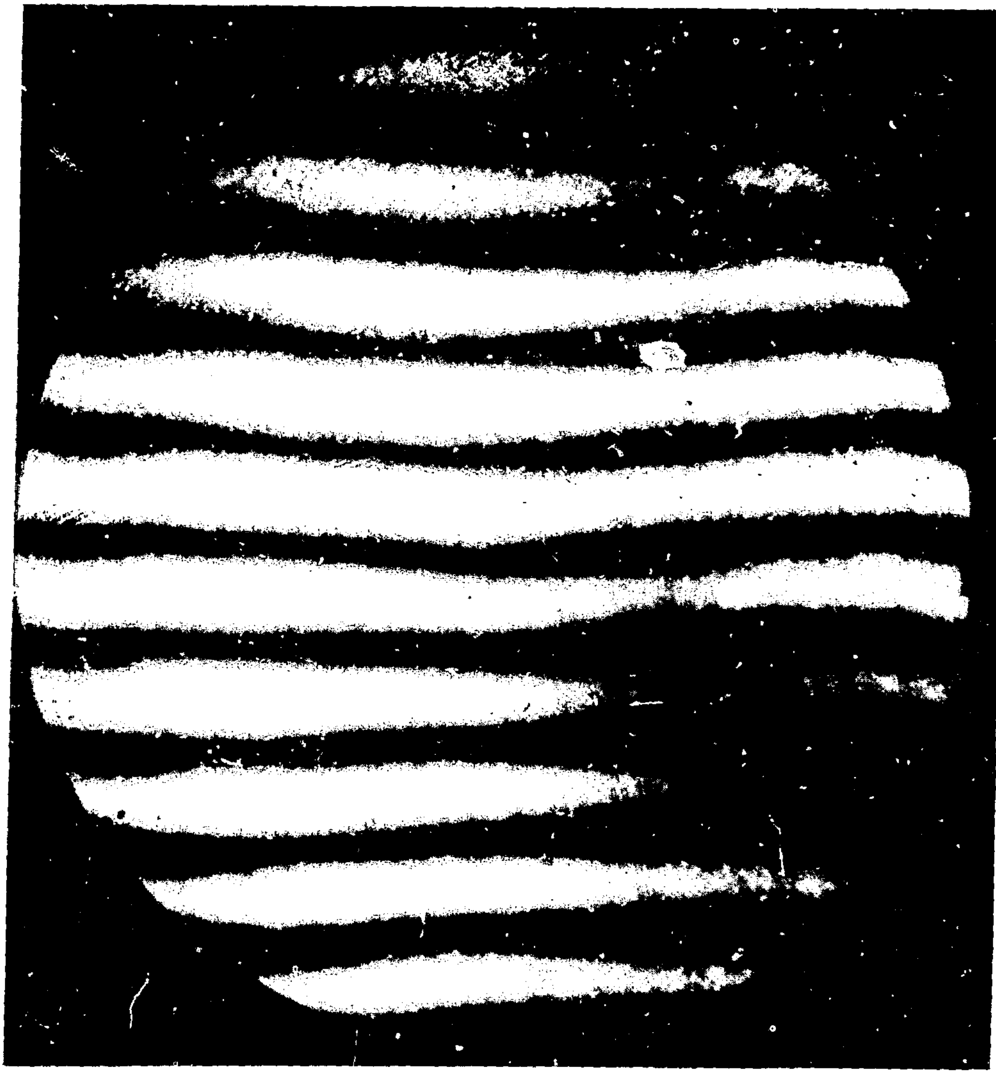


Fig. 4 - Interferogram (double pass at 633 nm) through 2-cm thick, 15-cm aperture KDP crystal, Cleveland Crystals

Another area of current development is massive, high-homogeneity, fused silica for the output windows of the crystal array and the focusing lens doublet. It appears that fused silica is the only material able to perform well at high energies at the third harmonic wavelength of 350 nm. For this reason, we are working with Corning Glass at their plant in Canton, New York and with Hereaus-Amersil in Hanau, Germany in order to establish acceptable quality levels and to determine production parameters for the fused silica components.

Advances in Optical Fabrication

In order to fabricate the numerous high-precision optical components for the Nova laser within reasonable cost and schedule, it was necessary to do a great deal of planning and facility construction with the finishing companies. From an optical manufacturing point-of-view, there are three basic types of surfaces: 1) lenses (both spheric and aspheric) 2) flat optics and 3) KDP crystals, which, although flat, have very special alignment requirements. They are being finished by single point diamond-turning.

Each Nova beam contains several lenses, the largest of which are the 80 cm diameter spatial filter, focusing, and diagnostic objective lenses. The spatial filter lenses, with focal length to diameter ratios of about 20, have asphericities of a few microns which are figured onto spherically polished surfaces. Fig. 5 shows an output spatial filter being inspected by the manufacturer; Fig. 6 is an interferogram of the same lens demonstrating the wavefront quality achieved.

The aspheric target focusing lens is a doublet with three spherical surfaces and one aspheric surface of about 50 micron deviation from the best-fit sphere; the diagnostic objective, a single component f/2 lens, has an aspheric surface which has a 1 mm deviation from the best-fit sphere.

For steep aspherics such as these, the modern method is to precisely generate the aspheric into the surface prior to polishing using numerically controlled machines; polishing is then done with the aid of driven flexible laps, also controlled numerically, using interferometric data as feedback. Steep aspherics are being manufactured by Tinsley Laboratories, Berkeley, California and Eastman-Kodak, Rochester, New York, both of whom have built special machines for the Nova project. Perkin-Elmer Corporaton, Norwalk, Connecticut is manufacturing the spatial filter lenses through the 50 cm size.

The large flat glass surfaces are being polished by continuous polishing machines, characterized by very rigid tables to hold the pitch flat to optical tolerances, very stringent thermal control of both the slurry and the surrounding air, and large truing tools to adjust the shape of the lap. The lap is an annular ring, with the width of the annulus about 1/3 of the diameter; for this reason the lap must be at least 3 times as large in diameter as the largest piece to be finished. No machines of the size and quality required were available at the beginning of the Nova project. Two manufacturers, Zygo Corporation in Middlefield, Connecticut, and Eastman-Kodak were selected, on the basis of experience in the field and competitive pricing, to build machines capable

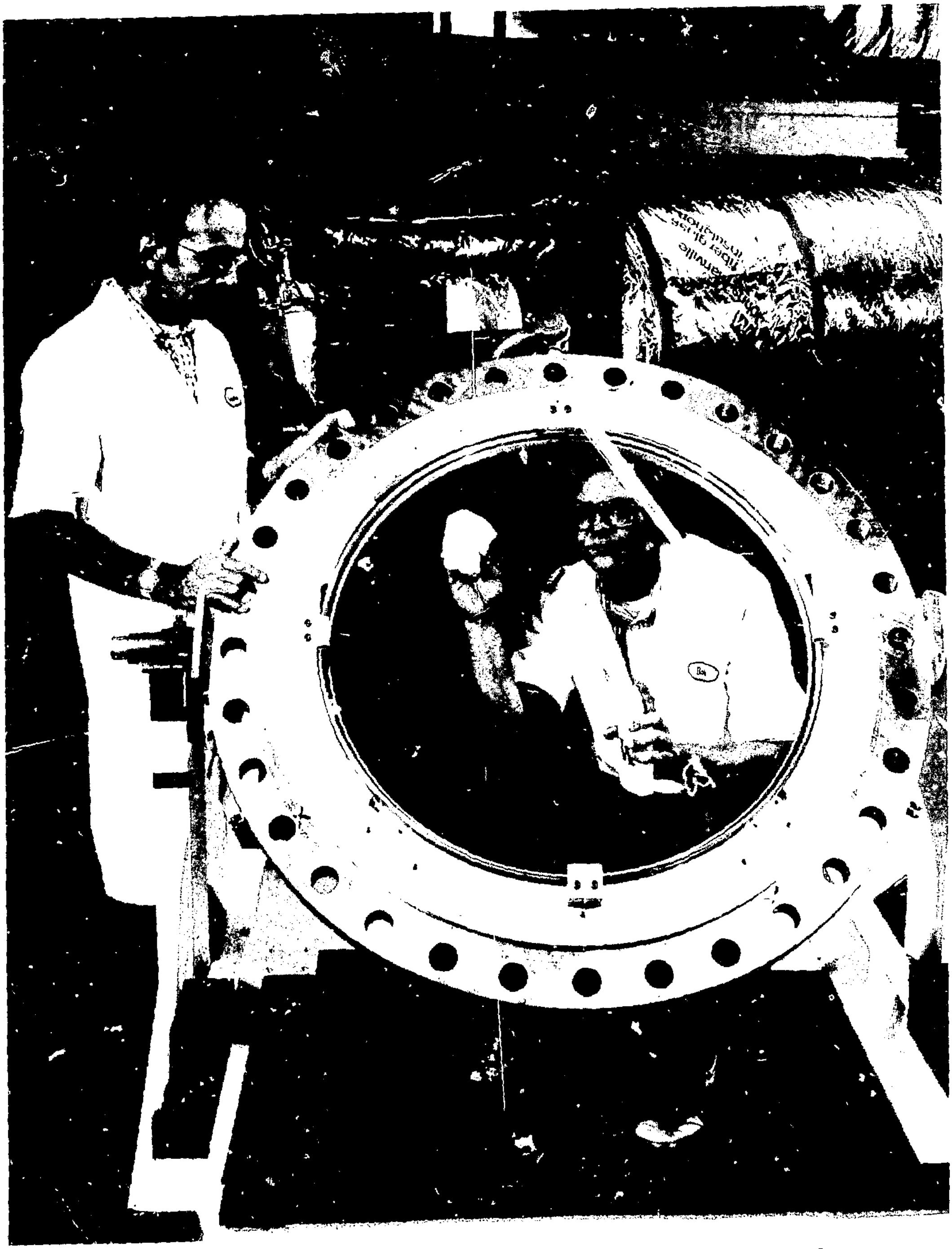


Fig. 5 - 80 cm dia. Nova spatial filter lens in test fixture, Tinsley Laboratories.

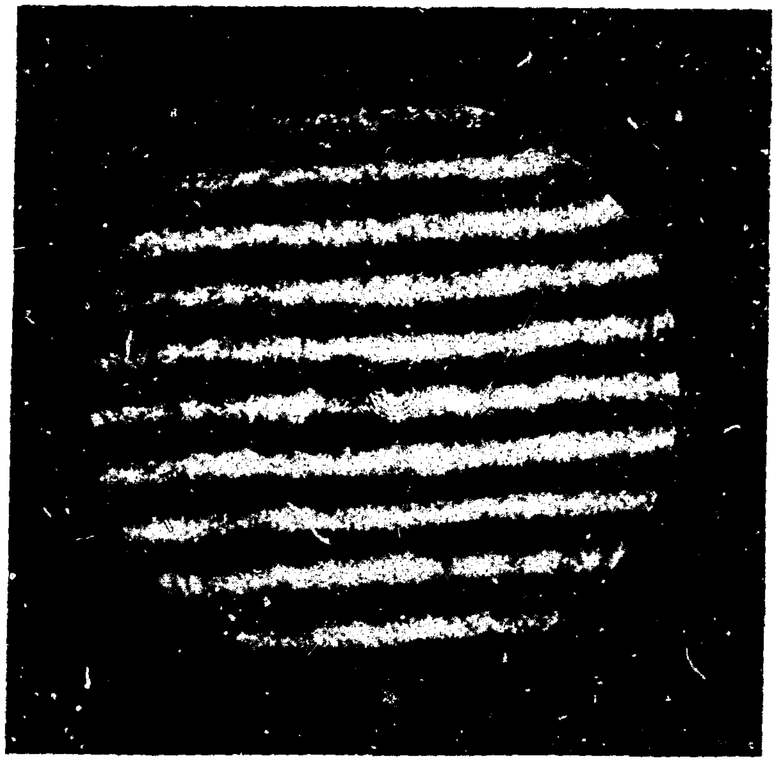


Fig. 6 - Interferogram (double pass at 633 nm) over 77 cm clear aperture of spatial filter lens, Tinsley Laboratories.

of doing the large flat optics. These machines are now in operation producing Nova parts. Flat lapping produces parts at approximately one-third the cost of more traditional methods.

It is also necessary when manufacturing precision optics to have adequate test equipment. Each one of these large machines has associated with it an 80 cm aperture Fizeau interferometer for the frequent parts checking required during the manufacturing process. These interferometers are located adjacent to the machines and kept at the same temperature. Fig. 7 shows the 12 foot diameter machine at Zygo Corporation.

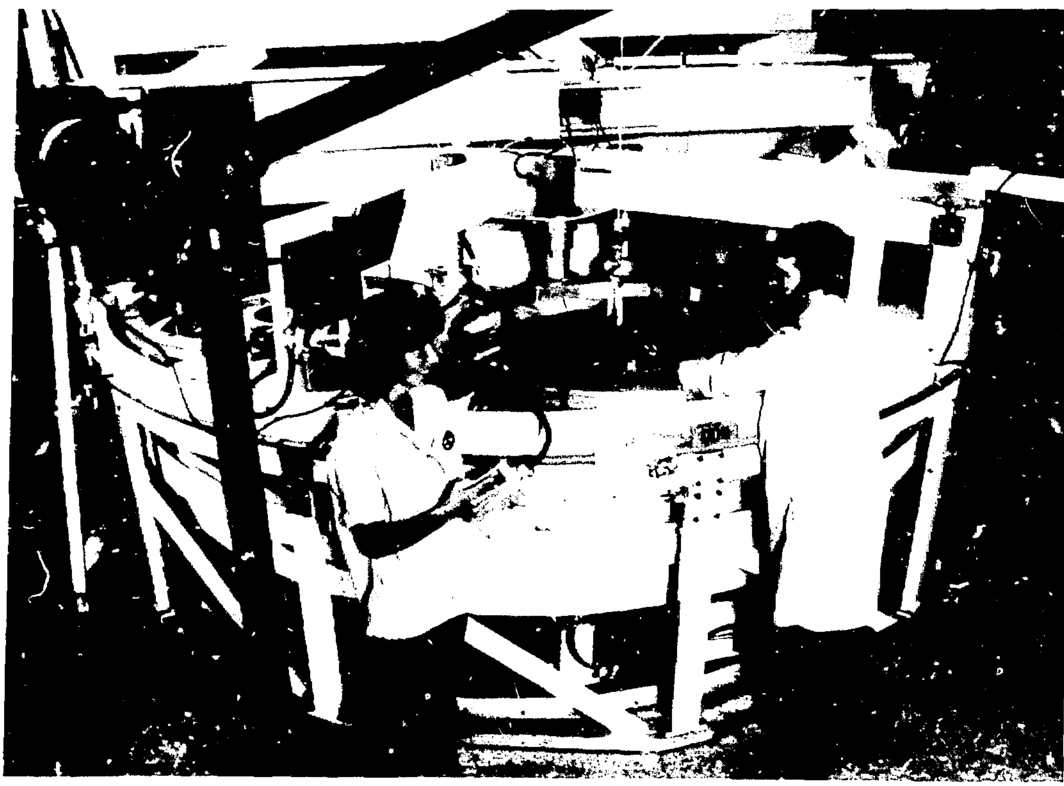


Fig. 7 - Twelve foot diameter flat lapping machine at Zygo Corporation.

Fig. 8 - 80 cm dia. interferometer at Zygo Corporation.

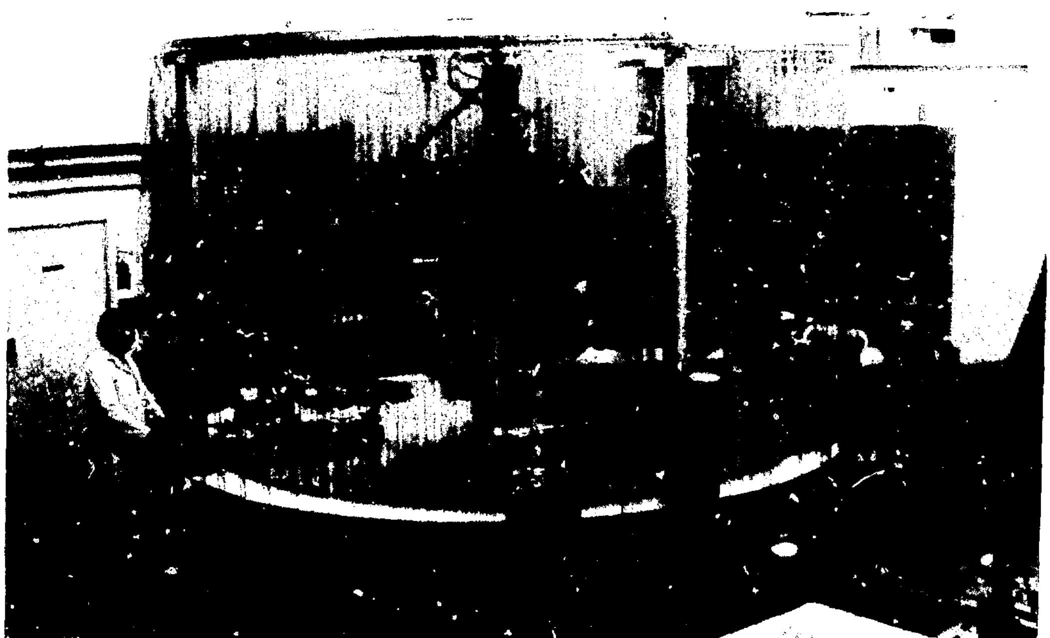


Fig. 9 - Fifteen foot diameter flat lapping machine at Eastman-Kodak

One of the newer technologies used in optical fabrication is single-point diamond-turning. Such technology can be very effectively used on metal mirrors of certain types and on plastics, but most glasses do not machine well. KDP, however, is much softer than glass. Experiments at LLNL determined that diamond-turning was a feasible approach to the machining of this material. One of the reasons that diamond-turning is so attractive for this purpose is that the KDP surfaces must be precisely oriented to the internal crystal structure so that the optimum phase match angle for each crystal is obtained when the crystals are assembled in a co-planar array. Another requirement for the array is to maintain very tight thickness control. Both of these requirements make diamond-turning of KDP much more efficient than would be the case if they were to be polished conventionally. The KDP diamond-turning technology, developed at LLNL has proved to be so effective that the crystal vendors are building diamond-turning machines for prefinishing the crystals. This is a less accurate requirement, but one to which diamond-turning lends itself very effectively. Currently the final diamond-turning is being done at Livermore, but it is our expectation that several commercial vendors will participate as production accelerates.

Coating

There are three basic kinds of coatings for the optical components. These are anti-reflection films on the air glass surfaces of such transmitting elements as spatial filter lenses, crystal array windows, and focus lenses, 2) polarizing filter coatings which are used in conjunction with Pockels cells and rotator glass to isolate various stages of the chain and 3) high-reflection coatings.

All coatings must be deposited with thickness control and uniformity comparable to the tolerances required for the wavefronts of the parts. This requires elaborately instrumented large high-vacuum coating systems and an array of monitoring equipment to control the process. LLNL has had built two high-technology chambers capable of handling these massive optics. Fig. 10 shows the 96" x 114" chamber at Spectra Physics, Mountain View, California and Fig. 11 shows the 120" diameter tank at Optical Coating Laboratories in Santa Rosa, California. The tank at Optical Coating Laboratories is capable of coating four of the large turn mirrors at one time.

Although these chambers are capable of all three types of coatings, one of the continuing problems in building large high energy lasers has been the damage threshold of anti-reflection coatings, where the full strength of the beam must propagate through the coating and the interface of the coating/glass surface. In order to find ways to increase damage thresholds of AR coatings, the research group in the laser program began a number of years ago to search for alternatives. One possibility was offered by leaching the surface of a phase-separated glass, thereby producing a gradient index which removed the Fresnel reflection. This techology was first introduced by Corning Glass to

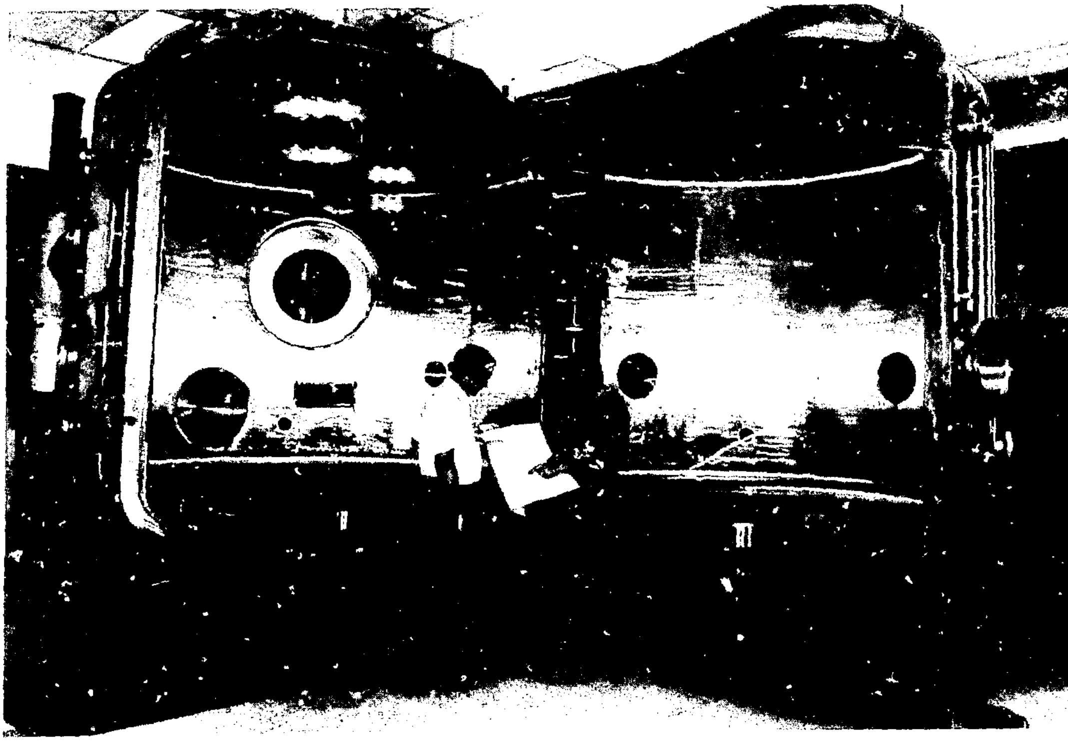


Fig. 10 - Large coating chamber at Spectra Physics.

Fig. 11 - Large coating chamber at Optical Coating Laboratories.

increase the efficiency of solar cell windows. With the participation of Corning, Owens-Illinois, Hoya, and Schott, we developed high quality glasses capable of meeting the stringent optical requirements while still permitting leaching of the surfaces. As a possible alternative solution, Schott extended earlier technology to treat the surfaces of ordinary borosilicate glass so that an anti-reflection surface would be produced. Both approaches have succeeded, and we plan to use them in Nova. This is an especially important advance for the input spatial filter lenses, where the flux is so high that traditional anti-reflection coatings can not be used. Now, we expect to be able to use coatings in lieu of bare surfaces, with a significant gain in laser efficiency.

The development of an anti-reflection coating for the fused silica output array window and the focus lenses remains to be accomplished. In the next two years we will be working with industry to develop a glassy material which can be applied to the outside of the finished fused silica optical components and then chemically treated to produce an integral anti-reflection surface.

5. NOVA POWER SYSTEMS AND ENERGY STORAGE

The Nova Power System 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 under actual operating conditions. Subsystems have met their individual requirements in various tests. Most parts are on order in quantities for the first half of the Nova System. One-hundred MJ of stored energy are required in the 3,100 high-power circuits which drive 3648 flashlamps and 62 Faraday Rotators. 25-30 MVA of peak AC power is drawn from the 13.8 kV 3-phase lines to charge the capacitance bank in 30 sec. Thirteen 1.5 MVA power supplies do the majority of the charging; twenty-one 100 KVA supplies do the rest. Switching is performed by 200 dual-ignitron switches. Control is provided by a computer hierarchy, with LSI/11 front-end processors and VAX computers for high level. Fiber optics is used throughout the contol system to avoid electrical fault and noise propagation. This chapter discusses the design approach used, the components selected, and the current status of the project.

Design Approach

The design approach on the Nova Power System has several facets. First of all the system has to be built within a cost envelope defined by scaling from the previous system, Shiva. Actual Shiva costs were used to develop the cost per joule of the system and of the individual components. These costs are used as bogies to stay within for the Nova system. Secondly, the system has to be an improvement on the reliability and availability of the prior system. The Shiva system was quite good with respect to reliability but in order to maintain the same level of performance with a substantially larger system, component reliability had to be improved. Maintainability was improved over the prior system as well. The physical size and large number of circuits in the Nova power system require that for rapid repair turnaround, care had to be taken in design on this point. The philosophy of operation is to be able to perform almost any needed repair between shots. Another aspect of the design approach is noise suppression. More than 18 megamps of current flows during the 1 ms pump pulse. The peak power is about 200 MW. In order to contain this power within the pulse power system, the pulse power common is isolated from the building by 25 kV and tied to building ground at one point. Normal and fault current is thus constrained to flow within the system unless a fault strikes the building ground. In this (infrequent) case, current flows through building steel to the substation and back into the pulse power system through pulse power ground. Instrumentation is isolated from noise by a network of isolation transformers. Another aspect of the design approach is most important: safety. The pulse power system is hazardous and much effort has been expended to make sure its operation is safe.

Circuit Description

A picture the basic circuit used for energy storage is shown in Figure 1. The schematic is shown in Figure 2. Each circuit is fused to limit fault energy to less than 50 kJ. Energy storage capacitors are bussed in parallel to achieve the desired capacitance. The series inductor is typically designed to give a pulse width of 450 microseconds (FWHM) and on underdamped waveform with a 10% reversal with the flashlamp impedance. The waveform temporal current peak matches the laser glass pump peak of flouresence for optimum pumping.

Table 1 gives the circuit parameters for Nova. The dual ignitron switch is placed in the ground leg so that many circuits can be connected to one switch. The coulomb limit for combined circuits is kept below 80 for the size D ignitrons. The circuit is charged through a 3900 ohm resistor as shown. A dummy load is switched in to replace the flashlamp for bank test. When the flashlamp is selected, the 5 ohm dummy load is connected in series with the spark gap across the inductor. This is done to prevent discharging the capacitors through the flashlamp directly through the spark gap in the event it has fired at the wrong time. which would cause the waveform to exceed the explosion limits of the lamps. The circuit sits in a plastic tray to provide insulation between the circuit common and the rack. This circuit is replicated 2,828 times in the Nova Bank.

Staging and Layout

Figure 3 illustrates the layout of the Nova Energy Storage System. 100 MJ of capacitors comprise the Nova bank. Nova 1 is housed in 16 rows, 53 feet long comprised of steel shelving allowing circuits to be stacked 7 high on each side of the aisle. Each circuit stores from 18 to 50 KJ of energy depending on the load requirement. Each circuit is packaged in a module with its own pulse-forming-network (PFN), and vacuum-formed plastic tray which provides 25 kV of isolation between the rack and the circuit common. The rack is set on insulators and tied to ground through a 1 kohm resistor. Each circuit has its own safety dump resistor. The dump circuits are mounted on a vertical channel adjacent to the capacitor circuit (see Figure 1). This vertical channel has up to seven dump circuits on it and is called a totem pole. At the end of each row of circuits are the switches for the circuits in the row. Up to five switches are located with a switch control rack which contains fire circuits along with computer interface and diagnostic circuitry. Table 2 gives the energy storage circuit count for the entire Nova bank.

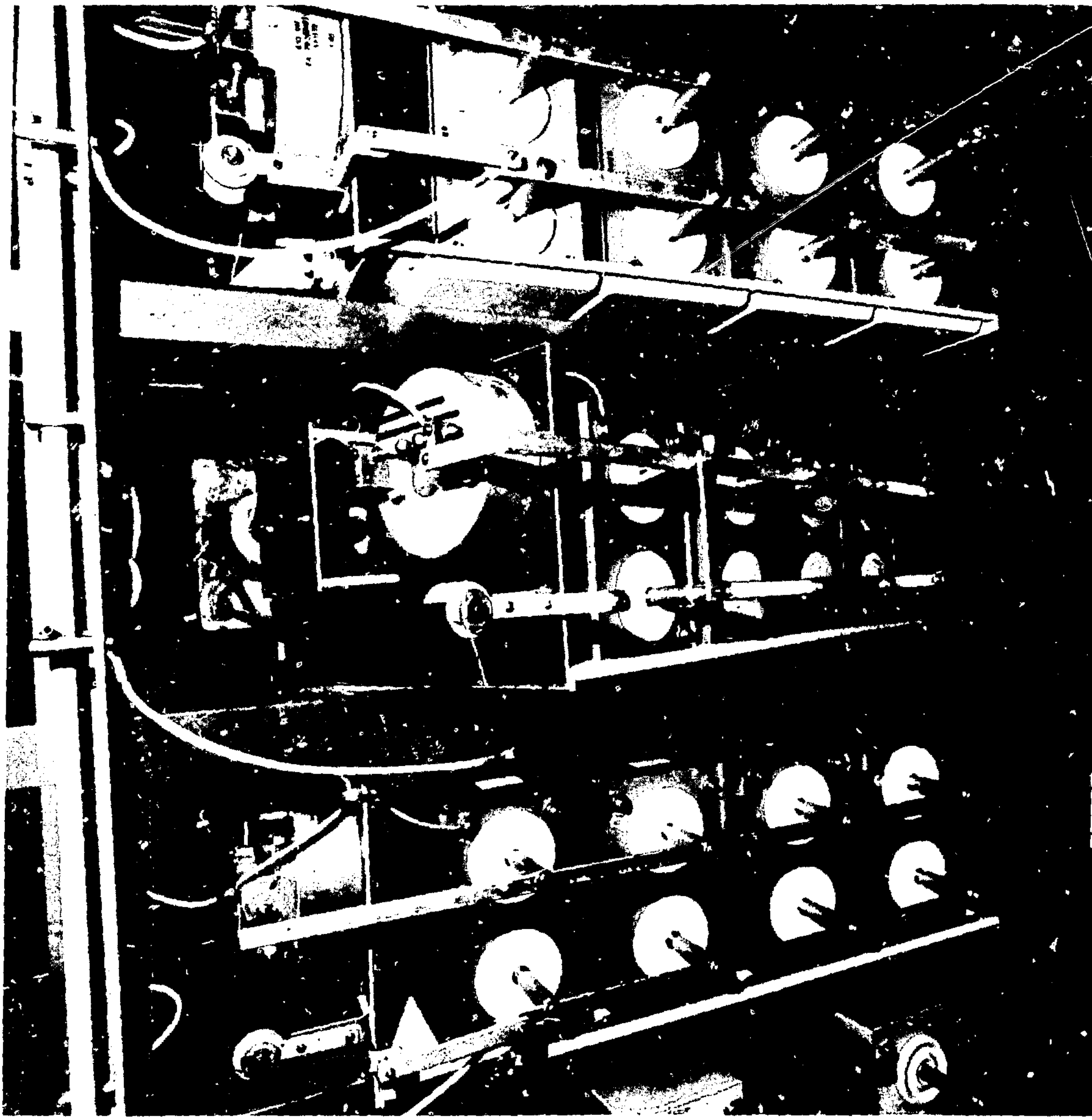


Fig. 1 - Basic Energy Storage Circuit

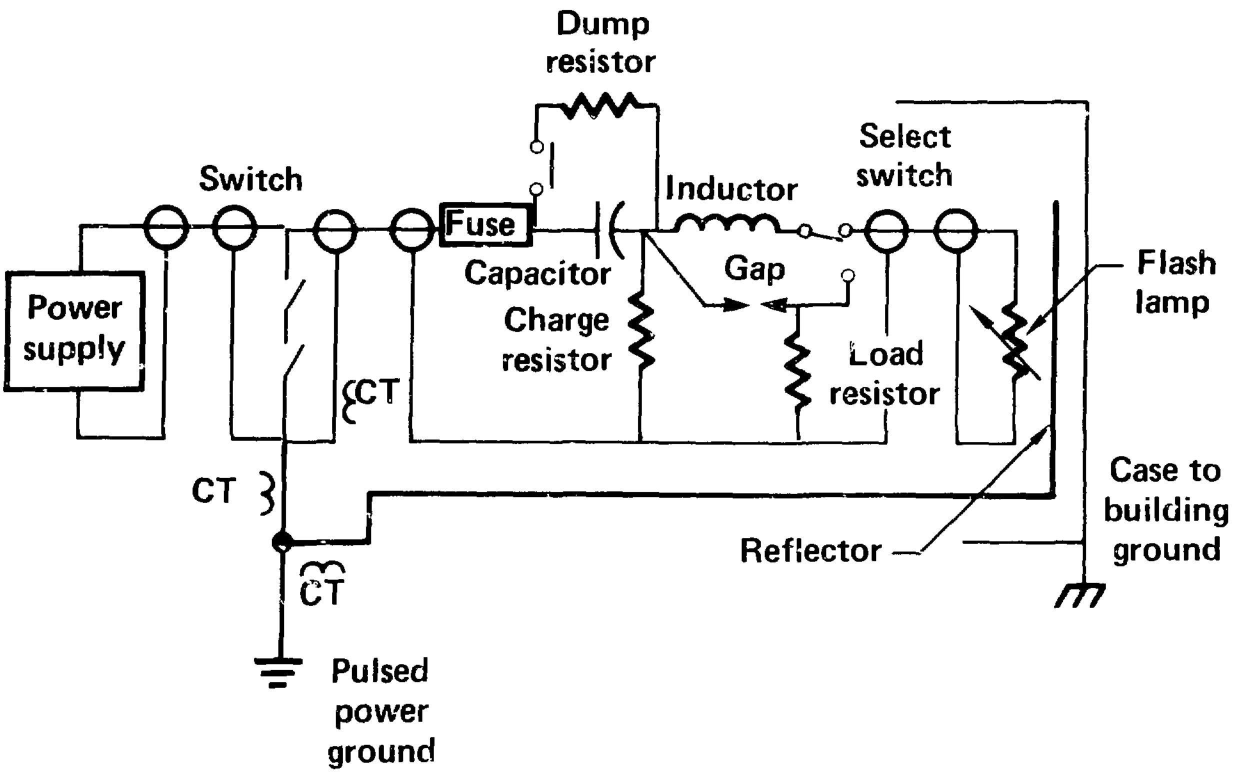


Fig. 2 - Schematic for Basic Concept

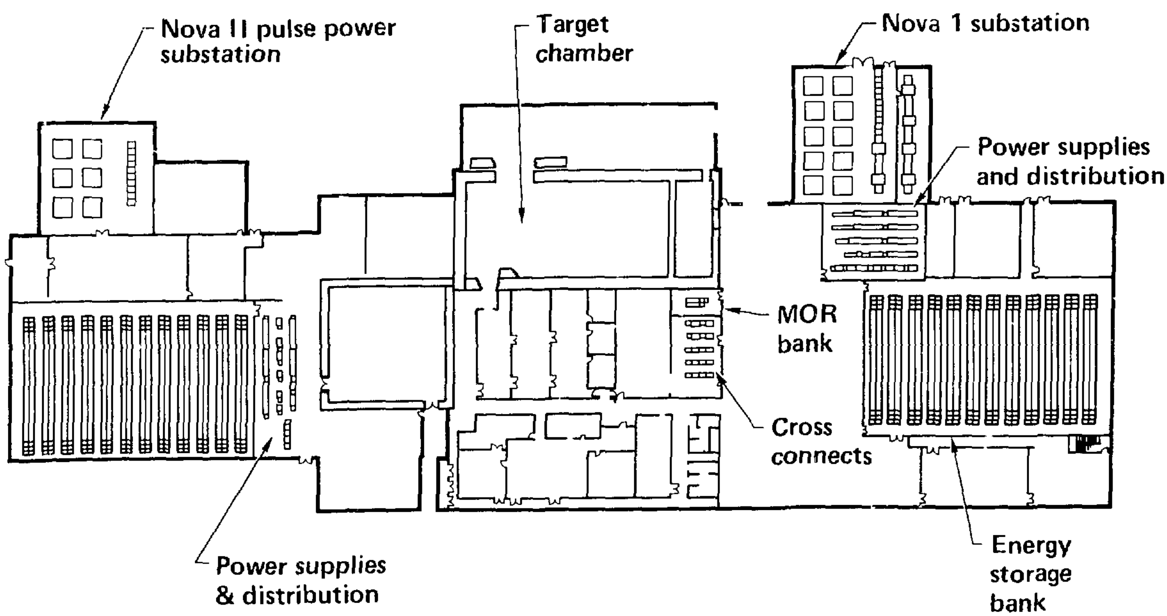


Fig. 3 - Layout of Nova Energy Storage System

TABLE 1. CIRCUIT PARAMETERS FOR NOVA

Component	Number of Circuits Per Chain Component	Capacitance Per Circuit (μF)	Inductor Size (μH)	Peak Current Per Circuit (kA)	Fuse Size Per Circuit (A)	Capacitor Type (kJ)
9.4 F.R.	1	101	None	5.53	7,000	3 (14.5 F)
15.0 F.R.	4	116	None	3.33	5,000	3
20.8 F.R.	5	200	None	2.60	3,000	5 (25 F)
31.5 F.R.	5	200	None	1.26	3,000	5
Rods	1	203	450	6.23	7,000	3
9.4	8	87	450	4.64	5,000	3
15.0	12	87	450	4.64	5,000	3
20.8	8	104	450	4.91	5,000	12.5 (52 F)
31.5	10	156	650	4.87	5,000	12.5
46.0	16	156	450	6.60	7,000	12.5

TABLE 2. NOVA CIRCUIT AND COMPONENT COUNT

Components	Number Per Arm	Number Total	Circuits Per Component	Circuits Total	Energy Per Component (kJ)	Energy Per Circuit (kJ)	Energy Total (kJ)	Lamps Per Circuit	Lamps Total
Rods	1	28	1	28	50	42+	1,176-3	6	168-19"
MOR	4								
Splitter	4								
9.4 Disc	2	40	8	320	174	18+	5,760-3	2	640-44"
9.4 F.R.	1	22	1	22	21	21	462-3		
MOR	2								
15 Disc	1	20	12	240	261	18*	4,320-3	2	480-44"
15 F.R.	1	20	4	80	100	24*	1,920-3		
20.8 Disc	3	60	8	480	200	25	12,000-12.5	2	960-44"
20.8 F.R.	1	20	5	100	200	40	4,000-5		
31.5 Disc	4	80	10	800	375	37.5	30,000-12.5	2	1,600-44"
31.5 F.R.	1	20	4	80	200	42*	3,360-3		
46 Disc	3	60	16	960	600	37.5	36,000-12.5	5	4,800-19"
				3,100 Total		5,666	16,998-3		4,968-19"
				282 F.R.		800	4,000-5		3,680-44"
				2,828 Disc		6,240	78,000-12.5		

Development Techniques

In order to develop a system of known reliability we constructed a 1 MJ test bank (see Figures 4 and 5) and have installed new designs in it as they became available. Three thousand cycles have been put on this bank with Nova circuitry in order to prove operation prior to quantity purchases. Before installation in the test bank, certain components went through separate test programs to establish their performance characteristics. The high density capacitors were one of these components. This test program is described in several given papers listed in the references.[1,5]

Another component that required a separate test program was the high power resistors. On Shiva these had the highest failure rate of any component. Over 20 vendors' products were screened and extensive testing performed to find cost effective resistors for dummy loads and dumps. The dummy loads are used as alternate loads for test of the energy storage system. The dumps are resistors used to absorb energy left in the capacitors after a shot. Dump resistors are rated at 1,000 ohms to give an RC time constant long enough to allow the mechanical dump mechanism to react and to keep the current low. These resistors must be capable of absorbing up to 200 kJ in a single shot under fault conditions. The dummy load is rated at 5 ohms and has similar energy requirements. Two vendors were found to make products that met these needs: Carborundum and Allen Bradley, LTD. Tests were performed that extended the data well beyond the operating point. Explosion energies were found for each component in the high power circuit. We have found by circuit modelling and test that normal operating levels in the bank are exceeded by large margins in fault conditions and in order to prevent propogation of fault damage, components must be very conservatively rated. Orders have recently been placed for dummy loads and dump resistors for the first half of Nova with Allen Bradley, LTD. Figure 6 shows the dummy load and dump resistors in a typical circuit installation.

Fig. 4 - Nova 1 MJ Test Bank

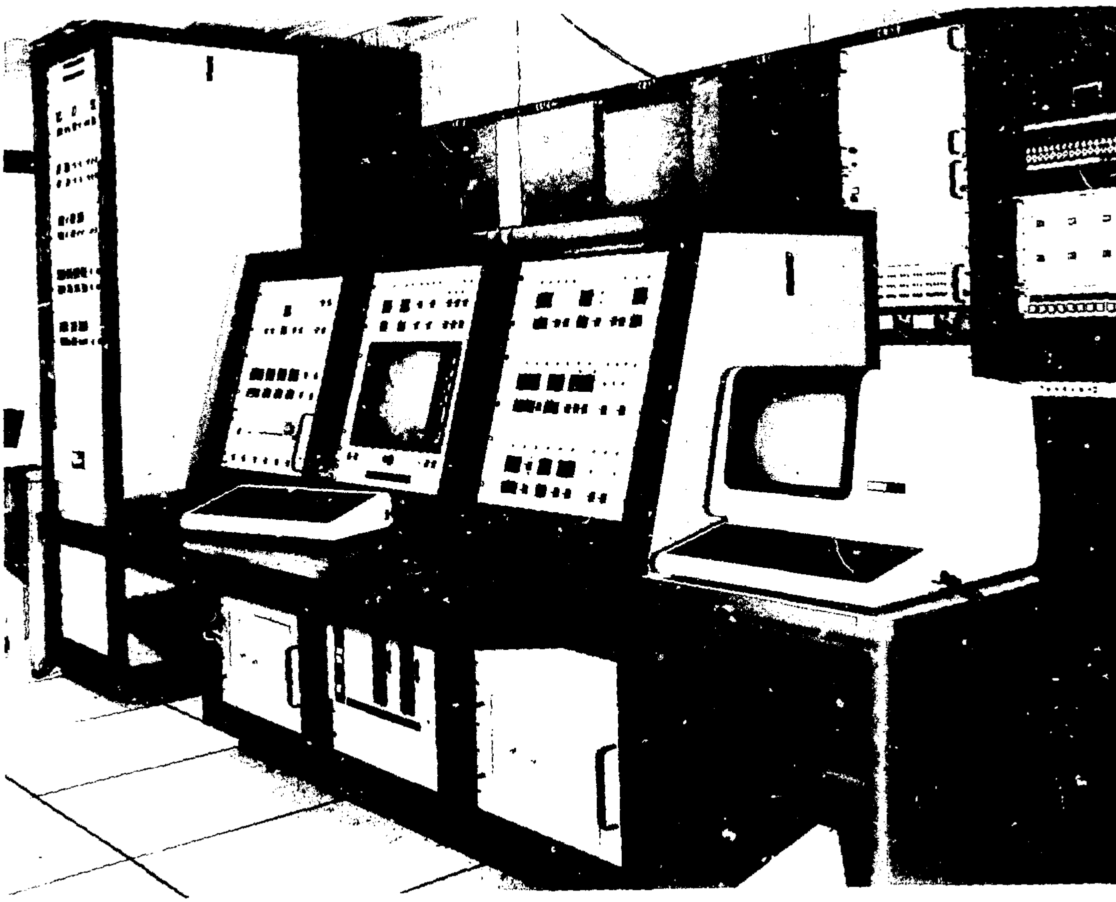


Fig. 5 - Nova Test Bank Controls

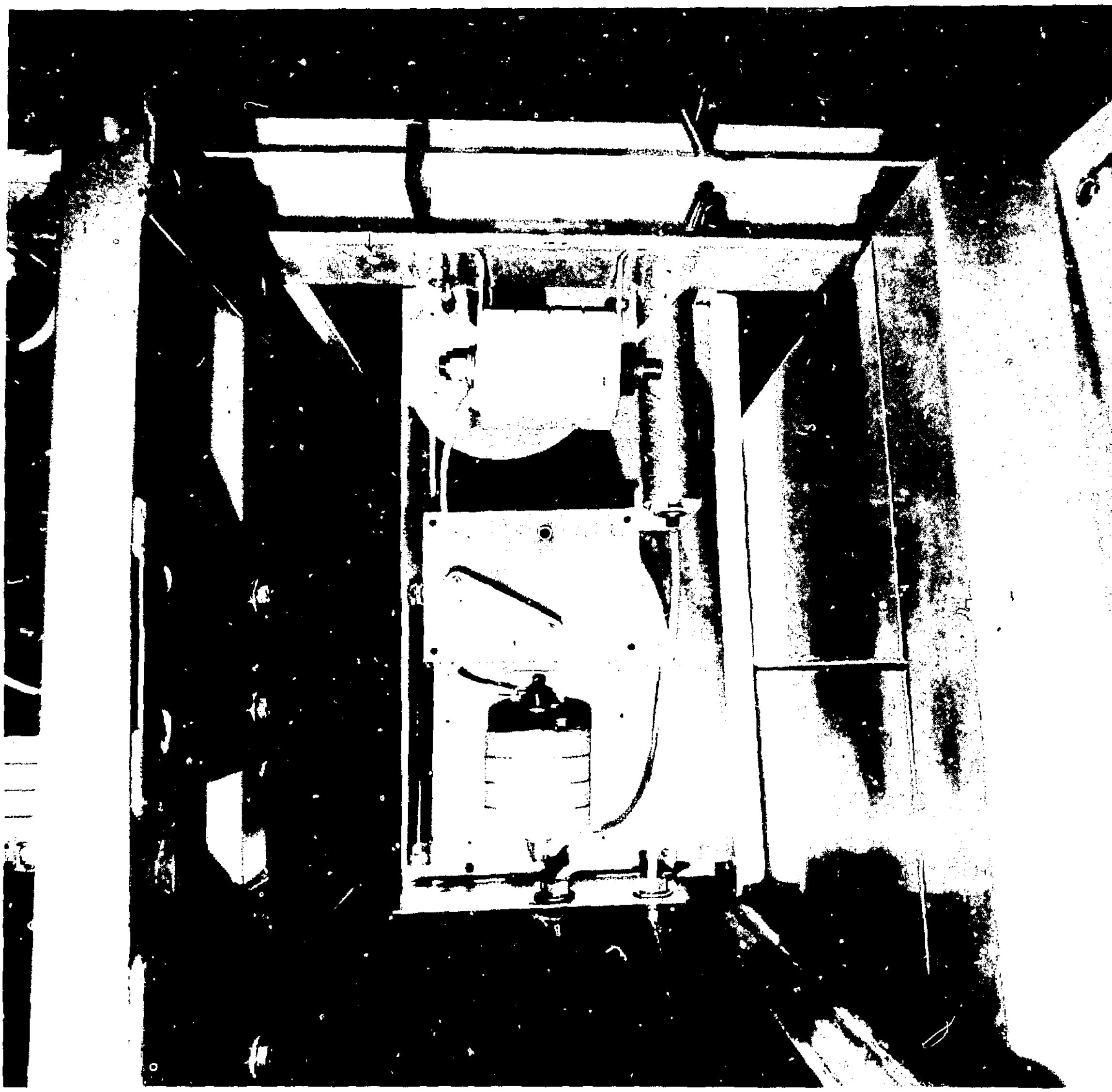


Fig. 6 - Dummy Load and Dump Resistors

Switching

The Nova energy storage system uses ignitrons for the switch element. Figure 7 shows a typical dual ignitron switch assembly. In order to ensure reliable operation of these tubes, a number of steps have been taken. The most troublesome aspect of ignitrons in a large population used for a system like Nova is their propensity for prefire. New tubes are now bought to a specification that sets a maximum prefire rate under incoming test conditions. In addition, the cathode of each tube is water cooled to 16-18 degrees C, and the anode is heated to 50 degrees C. Anode heating was accomplished in the past by heat lamps. On Nova, direct contact heaters powered by isolation transformers are used. This reduced the power consumption from 500 watts per tube to 26. In addition, to prevent prefire, two tubes are placed in series in each switch and a voltage divider is used to equalize tube voltage. Periodic high potting to 25 kV ac is also performed to check the condition of each tube. In order to detect and localize any prefire that might occur, a voltage monitor is placed in each switch rack. This monitor is fiber optic coupled to the control system, so if a prefire occurs the event is immediately recognized and action is taken. Ignitor failure is another failure mode of ignitrons. On Nova, both ignitors on each tube are fired on each shot, and current transformers monitor each trigger. This trigger information is fiber optic coupled to the control system as well, so that failures can be localized and repaired quickly. A large current transformer, called a stem bug, is used to monitor the main switch current as well, so that each switch is fully diagnosed.

In the Nova system, effort was made to separate the power conditioning system physically as much as possible from the laser, both for safety and in order to operate the bank as a separate entity for test and debug. For this reason the bank diagnostic system, LCD, and its sensors, current bugs, are located in the bank. The current bugs are located in the switch and monitor current flowing in the power conditioning ground leg of each lamp circuit. This choice was made to be able to monitor all high current fault modes associated with flashlamp circuit failures.

Two hundred dual, size-D ignitron switches are used in Nova. An integral number of amplifiers must be connnected to an individual switch to prevent partial firing of an amplifier's flashlamps and possible damage. The switches are staged so that individual beam lines may be fired. The largest amplifiers have 46 cm aperture for the laser beam and use 80 lamps each connected 5-in-a-series in 16 circuits. At present the subassemblies are designed. Long lead orders have been placed, and orders for ignitrons from three vendors for qualification to the new specification are in process.

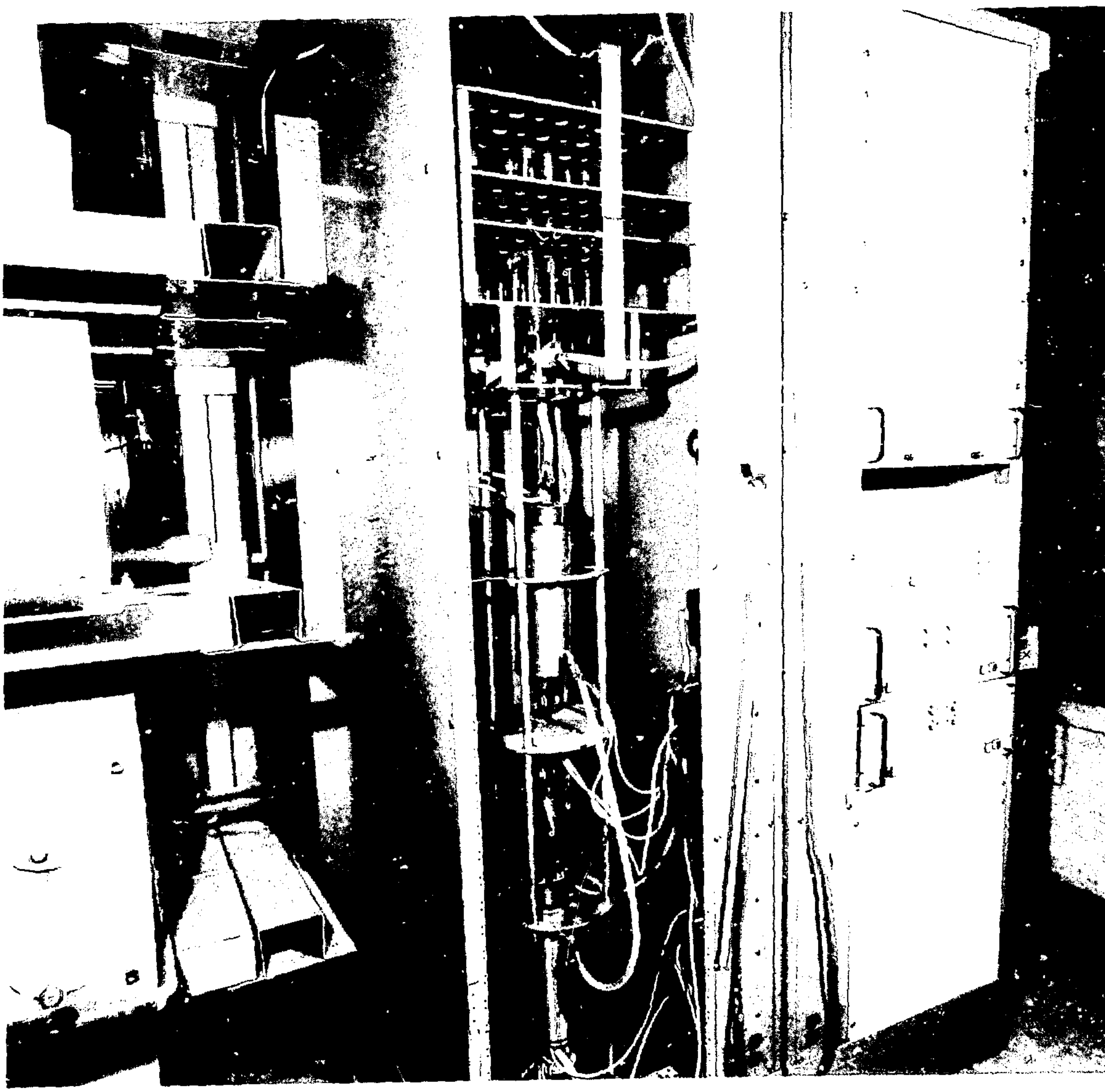


Fig. 7 - Ignitron Switch Assembly

Power Supplies

To charge the Nova bank within 30 seconds as required for adequate bank lifetime, 25 to 30 MVA of dc power must be applied to the bank. Large substation sized power supplies have been designed to supply this much power at an efficient cost. Smaller, Shiva-type, 100 KVA supplies will be used to charge the modules for the rod amplifiers and rotators, but most of the bank will be charged by 12 large supplies (plus one spare) located in the substation areas outside the Nova Lab Building.

All of these supplies are designed as three-phase voltage doublers. Each large supply is capable of charging 12 MJ of capacitors to 22 kV in thirty seconds. They are powered via a fused disconnect from the 13.8 kV ac power mains, and draw approximately 2.0 MVA peak power. A picture of a typical Nova power supply is shown in Figure 8.

There are differences between these and the 100 KVA supplies. These MVA supplies are electrically 15 times larger than the smaller units. They use oil cooled transformers and rectifiers, while 100 KVA units are all air cooled. The control element is a vacuum contactor on the primary which eliminates costly silicon as on the 100 KVA units. Due to economy of scale and the use of contactors, the estimated cost of the Nova supplies is $0.08/VA vs $0.15/ VA for the 100 KVA units, (both in constant dollars).

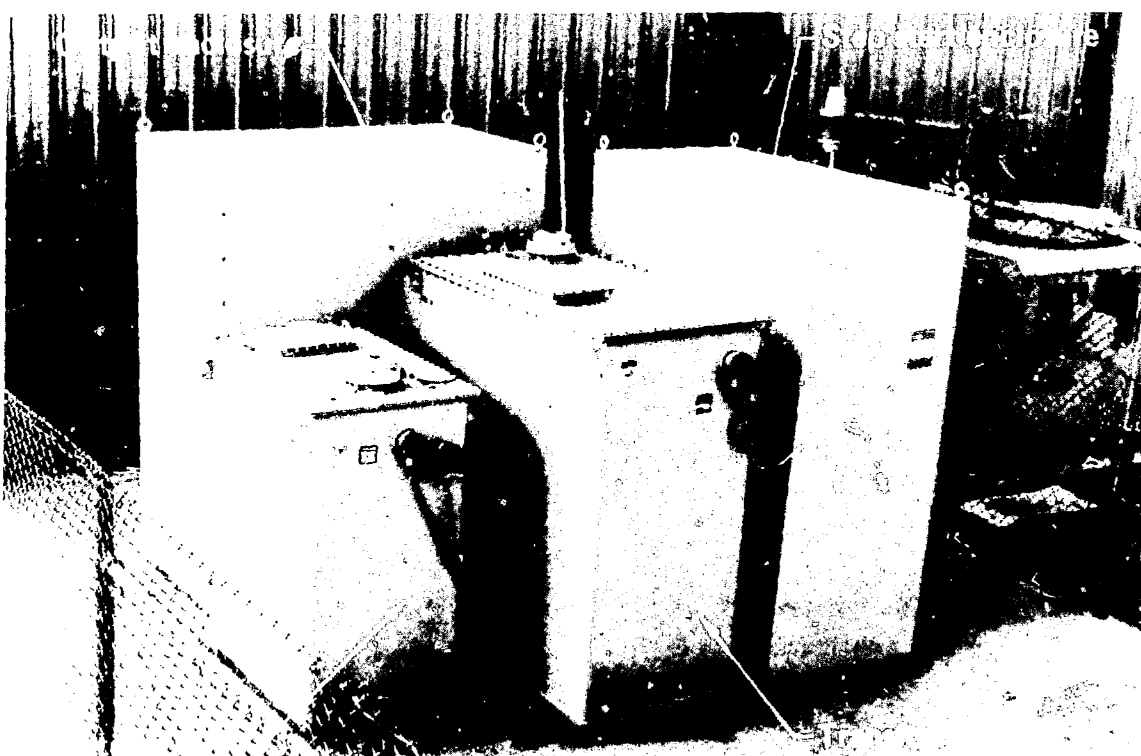


Fig. 8 - Nova MVA Power Supply

Table 3 lists the power supply allocation and charge times for the various parts of the Nova bank. The order for seven large Nova power supplies has been placed with Aydin Engineering of Palo Alto. The first unit has been throughly tested and has over 3,000 charge cycles on it. The second unit is being delivered in October 1981. The remaining six units for Nova I are to be delivered this calendar year.

Optical Isolation

Optical isolation is required in the laser chain to prevent spontaneous amplification of noise (ASE), to prevent oscillation from building up, and to prevent reflected power from damaging components. Isolation is provided by three basic techniques: Pockels cells for small apertures, Faraday rotators for apertures up to 35 cm, and plasma shutters for larger apertures. Pockels cells use electrically active crystals in a switched electric field to redirect reflected power. Faraday rotators use the Faraday effect in doped glass to redirect reflected power. Plasma shutters use exploding wire technology to place a blocking plasma in the way of reflected glass.

In order to pulse the Pockels cells in the nanosecond regime, a number of techniques have been used. Pockels cells in the laser chains must each be switched simultaneously. For Nova, an N-way fanout was designed to be switched with a hydrogen thyratron. Risetime is 15 ns, adequate for chain Pockels cells. In the case of Pockels cells near the oscillator front-end, the risetime must be maintained at 1-3 ns with 200 ps jitter. For this application, planar triode pulsers are used. The planar triode is a 3000 MHz device which can be operated in a switched mode. In this mode, for 5-25 ns pulses, the rated cathode current can be greatly extended and a single tube is capable of putting out 30 amperes with several kilovolts of anode swing. Reference 2 gives the application in greater detail. Figure 9 shows a planar triode pulser chassis.

The Faraday rotator (F.R.) pulse system is very similar to the flashlamp system with the exception that the circuit uses no inductor for pulse shaping. The load is the coil in the rotator body that generates the magnetic field. The LC of the energy storage and the load coil would ring at about 9 kHz if the backswing diode was not used. The ringing would not be deleterious to the rotator's performance since there is sufficient time at the first current peak to satisfy system requirements, but the ringing exchanges a great deal of charge through the switch and many additional switches would be required were the diode not utilized. Table 1 gives the circuit detail for the several Faraday rotators in the Nova System. Table 2 gives the number and location of rotators in the Nova Chains.

The plasma shutter pulse power system has been described in detail elsewhere.[3,6] In summary, it utilizes four uv preilluminated rail gaps, low inductance capacitors, elastomer dielectric system, and coaxial geometry to obtain the required 650 kA in 400 ns in a small package that fits in the laser chain. The system has been successfully tested on a Shiva arm and has stopped Nova intensity beams in the time frame required.

TABLE 3. POWER SUPPLY ALLOCATION FOR NOVA

Component	Type of Supply	Number of Supplies	Energy Per Supply (kJ)	Total Energy Per Component (kJ)	Capacitance Per Supply (μF)	Charge Voltage (kV)	Charge Time (sec)
Rod	KVA	3	600	1,400	4,466	22	41.85
			600				
			200		812		7.61
9.4 F.R.	KVA	3	210	462	1,015	20	7.62
			210				
			42		203		1.53
15 F.R.	KVA	2	1,000	2,000	4,640	20	34.80
20.8 F.R.	KVA	4	1,000	4,000	5,000	20	37.50
31.5 F.R.	KVA	4	1,000	4,000	4,640	22	43.48
9.4 Disc	MVA	2	6,090	12,180	34,800	22	21.74 (43.48)
15 Disc							
20.8 Disc	MVA	2	6,000	12,000	24,960	22	15.59 (31.18)
31.5 Disc	MVA	4	7,500	30,000	31,200	22	19.49 (38.98)
46 Disc	MVA	4	9,000	3,600	37,440	22	23.39 (46.77)
Spare	MVA	1					
PILC	KVA	2					

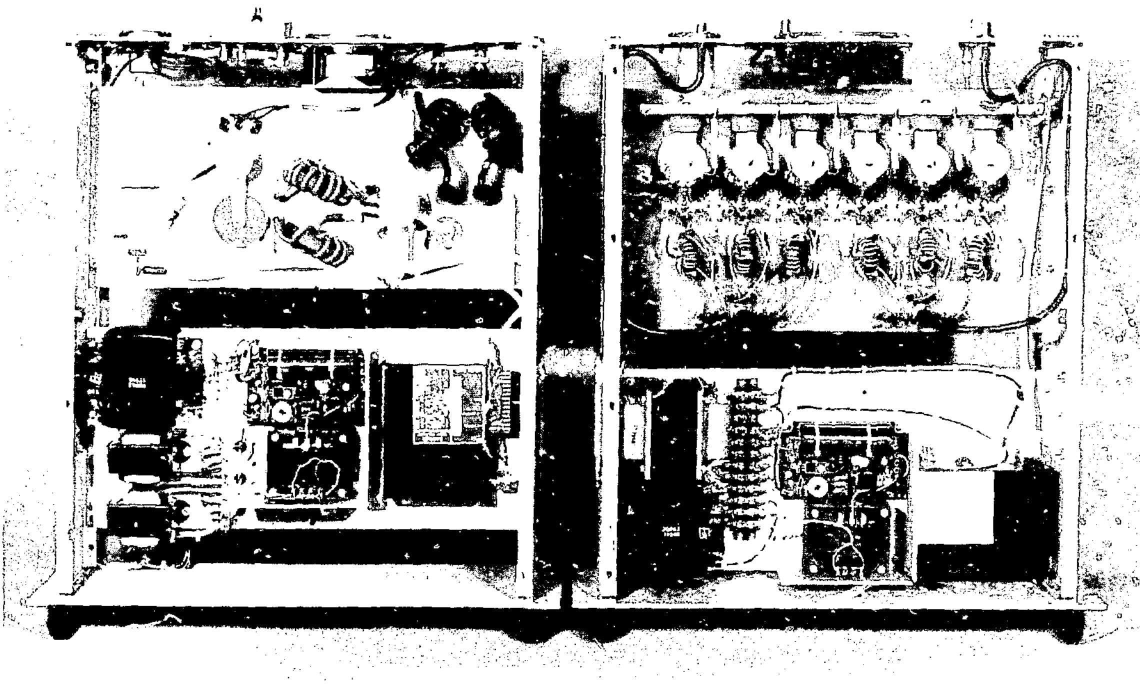


Fig. 9 - Planar Triode Pulser Chassis

Control

The pulsed power system is controlled and monitored by a computer system illustrated by Figure 10. The central control computer is a DEC VAX-11/780. The operator controls the system through a CRT display/touch panel and selects control functions through a series of menues. The VAX responds by generating a series of comands to the hardware devices. These commands are put in a memory shared with LSI-11/23 front-end processors. They route the commands to the hardware through fiber optic links. The FEP constantly polls the hardware devices for status information and places it in the common memory. The control computer thus has visibility of the system status all the time.

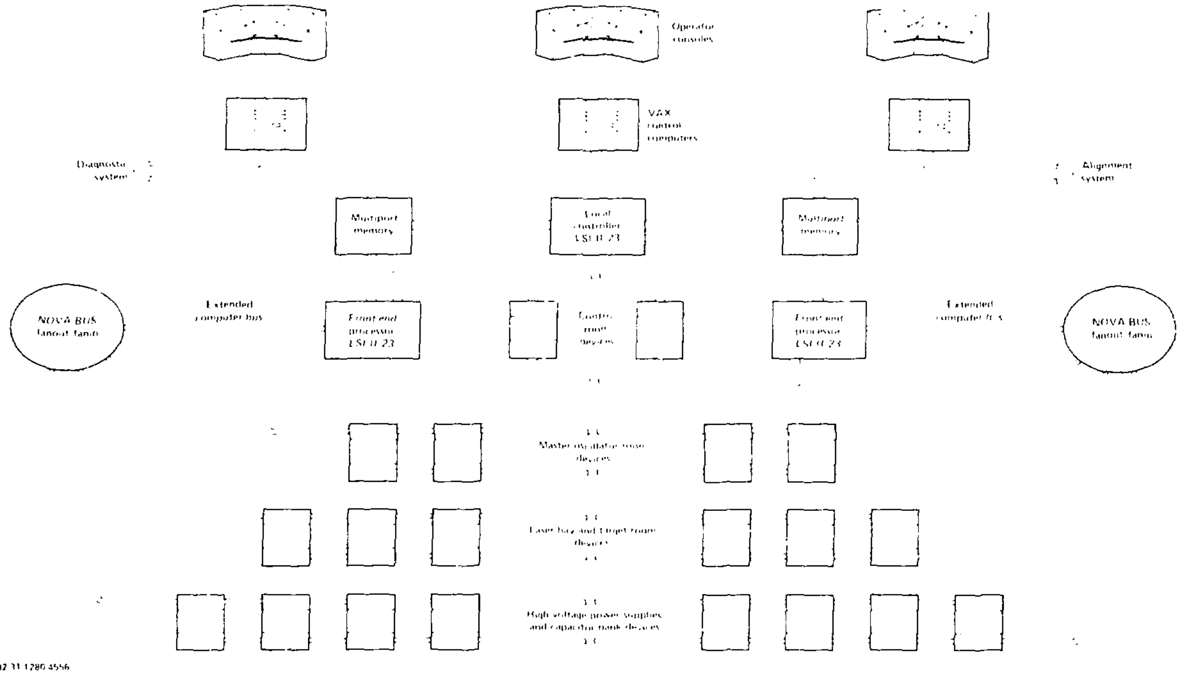


Fig. 10 - Pulsed Power Control System

Pulsed power devices are connected to the FEP's in a redundant fashion. The FEP's internal bus is serialized and extended to service numerous devices. The interconnection network is called "Novabus" and divides the devices among 12 parallel chains.

Communication between the computers and the pulsed power devices takes place in a hostile environment of high voltage, high currents and extreme EMI fields. Additionally, the communication system provides isolation between devices. Using fiber optics as a communication medium resolves the isolation requirement but does not satisfy the noise immunity requirements. Optical communication is inherently immune to EMI but the conversion process from optical to electrical is noise sensitive. This is especially true if the data rate (bandwidth) is high and the optical flux is of low intensity. The Nova control system operates at 10 Mbps with an optical flux of 10 watt. Shielding of the optical receiver has been tried with limited success. The resolution of the noise immunity problem for Nova is to store command scheduled to occur at peak noise periods in the device interface electronics. Thus during the time of high noise levels, optical to electrical conversion errors do no effect operation of the system.

Figure 11 illustrates the interface between the control system and an ignitron switch. Note that the pulse power elements are electrically isolated from the control electronics. Triggers to the ignitron are sent via fiber optic cables and current transformers around the ignitron leads and the ignitron itself provides feedback to the control system via fiber cables. Attached to each flashlamp lead is a current transformer which is wired to a lamp circuit diagnostic chassis (LCD).

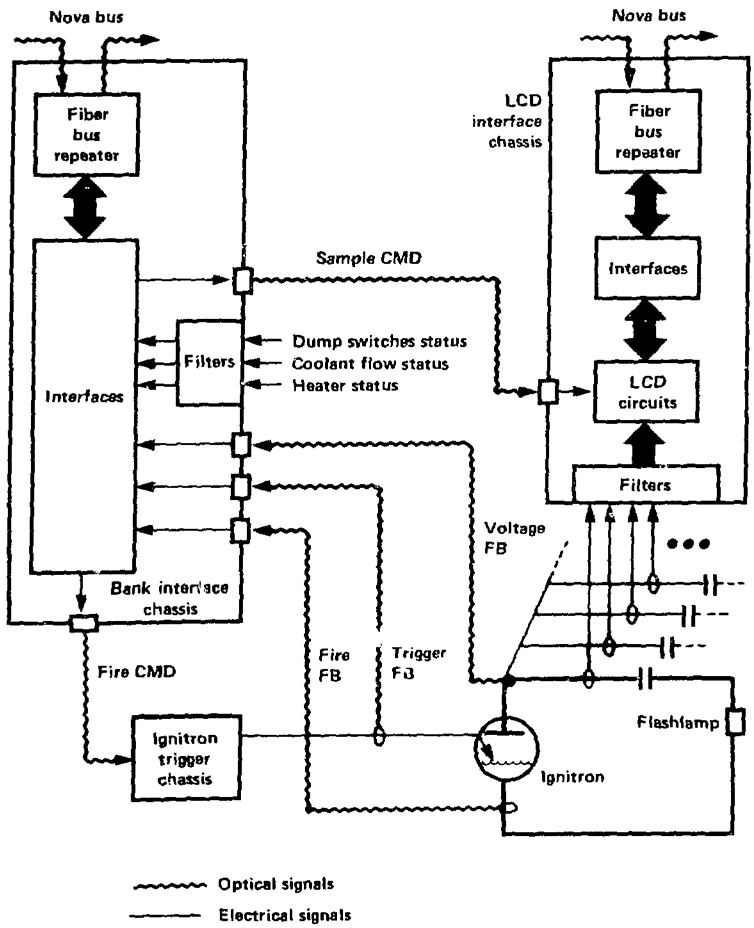


Fig. 11 - Ignitron Control and Monitor

At shot time, the current waveform of each flashlamp is sampled, digitized and stored in LCD memory. This data is later transferred to the VAX computers for processing and identification of anomalous conditions. Abnormal waveforms are plotted and presented to the test director as hard copy or CRT plots.

The control system design is nearing completion and all critical items have been tested as part of the 1 MJ test bank. Over 1,200 circuit boards have been ordered and completed chassis will be fabricated beginning in December 1981.

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6. NOVA FRONT END SUBSYSTEM

The Nova front end is designed to provide highly reliable input pulses for each of the 20 amplifier chains with adequate drive and flexibility to provide all the required output variations of the total Nova laser.

The front end of the Nova laser consists of all beam line components ahead of the 20 amplifier chains. It is subdivided into a master oscillator room (MOR), where initial pulse generation and pre-amplification occur, and a splitter array (SA) which splits and transports the MOR output to each chain. Figure 1 shows the front end beam lines relative to two of the four laser space frames.

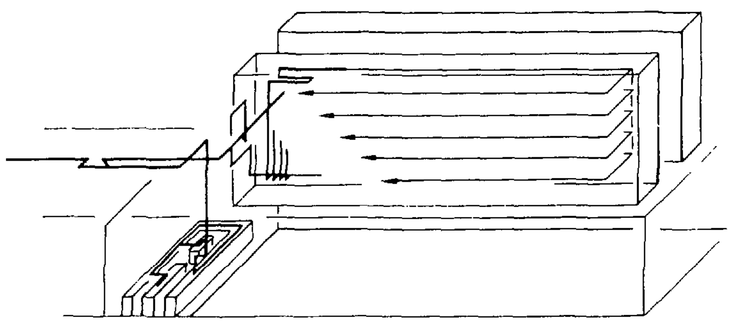

Fig. 1 - Schematic representation of The Nova front end in relationship to two of the four laser space frames.

The function of the front end is to generate and distribute appropriate pulses to each of the 20 amplifier chains. Great flexibility is required because all variations in pulse properties on target are initiated in the front end. Variations in total output energy or temporal pulse shape are accomplished in the MOR. Variations in the relative distribution of output pulse energy from the 20 chains and variations in their relative arrival time on target are accomplished in the SA.

Total system performance depends on the proper functioning of the front end, making front end reliability extremely important. A single failed front end component, for example, degrades all 20 beams, whereas a component failure in a single arm affects at most 5% of the system output. The flexibility required of the front end also contributes to the reliability problem by introducing a large number of adjustable components.

Front end reliability has been addressed by emphasis on component and function reliability as well as by efforts to improve maintainability. Automatic alignment systems and computer monitoring of adjustable components directly improve reliability. Component layout for accessability and the staging of beam diameters for a minimum of different parts improve reliability by improving maintainability.

The Argus and Shiva laser fusion facilities at Lawrence Livermore National Laboratory have demonstrated the need for a functionally separable front end. Preparation for a target shot involves detailed and lengthy procedures for the front end as well as for the amplifier chains and target area. Functional separability allows the front end to be set up in parallel with main chain and target preparation. It also provides for front end maintenance time during busy shot schedules, a necessity for maintaining reliability. Consequently, as many of the Nova front end functions as possible are performed in a totally separate room, the MOR, that is functionally separable from the rest of the system.

Master Oscillator Room

The MOR is isolated physically in the basement, beneath the optical switchyard as indicated in Figure 1, and next to the main control room. It has complete local control capability to free it from main control room operations. Its energy storage area is separated from the main energy storage to allow independent maintenance. All communication between the MOR and the rest of the system uses fibre optics, except for a few diagnostic channels. It has its own air handling equipment to maintain a class 10,000 clean room environment to minimize particulate contamination problems. The result is a stand alone subsystem which can independently be maintained and prepared for target shots.

The MOR must be a highly versatile and reliable laser system by itself to properly drive the NOVA amplifier chains. The required range of MOR output pulse properties includes temporal pulsewidths from 0.1 to over 10 ns and pulse energies from 10^{-4} to over 30 joules. Additionally, its output must be spatially uniform and free of prepulse energy injected into the chains prior to the main pulse. Two MOR subsystems provide these functions, an oscillator system for initial pulse formation and the MOR preamp.

The oscillator system requires two oscillators to provide the necessary range of output pulsewidths. A mode locked oscillator provides pulsewidths from 0.1 to 1.0 ns in duration, and a single longitudinal mode oscillator provides the longer pulses. Both were specifically developed at LLNL for fusion lasers and have been successfully used on Argus and Shiva.[1]

The mode locked oscillator produces a train of output pulses with the width of the individual pulses determined by the oscillator. A switchout selects a single pulse from this train for amplification. Figure 2a shows the total pulse train from the oscillator, the unwanted portion rejected by the switchout, and the single output pulse.

The single longitudinal mode oscillator produces a smooth output pulse from which a portion is "chopped" by a pulse slicer as shown in Figure 2b. Here the open time of the pulse slicer determines the output pulsewidth, not the oscillator. The two oscillator outputs are combined on a polarizing beam splitter and aligned to the preamp beam line. A computer controlled polarization rotator following the polarizer selects either output for amplification.

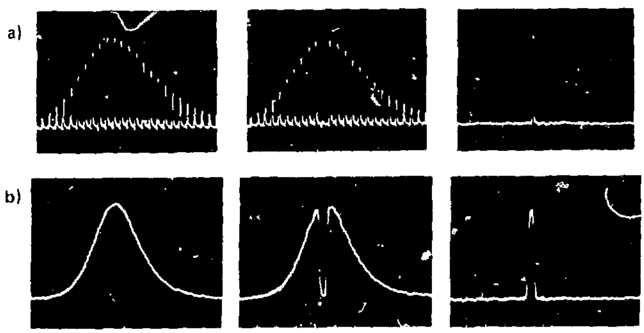

Fig. 2 - Representative waveforms from the two types of oscillators used in the Nova oscillator system.

The MOR preamp increases the pulse energy from the oscillator system to as much as 30 joules and shapes the pulse spatially for the main amplifier chains. Two 1.0 cm diameter and four 5.0 cm diameter rod amplifiers provide a net small signal gain of 10^7, enough to reach the maximum safe fluence at the output optics for all pulsewidths. Fast optical shutters, consisting of a Pockels cell between crossed polarizers, isolate the amplifiers from one another to prevent self oscillation. Adjustable attenuators between amplifiers provide gain variation, eliminating the need for individual control of the charging voltage for each amplifier.

Adjustable attenuators consist of a half-wave plate followed by a crossed polarizer as shown in Figure 3. Rotation of the half-wave plate changes the polarization direction, controlling the fraction transmitted and reflected from the polarizer. This same combination also provides an adjustable beam splitter and, when reversed, a means of combining two separate beam lines. All half-wave plates are computer controlled to facilitate changes and logging of settings.

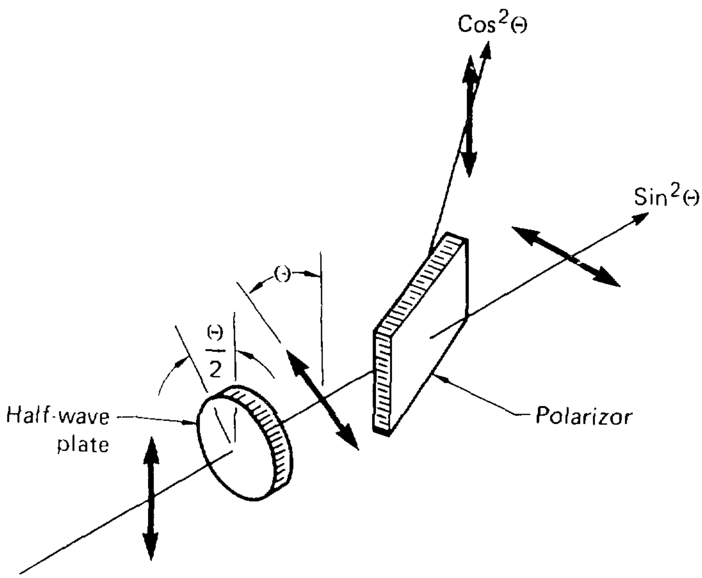

Fig. 3 - Adjustable attenuator or beam splitter.

Efficient energy extraction in the amplifier chains requires spatial shaping of the Gaussian profile from the oscillator system. A Gaussian spatial profile uses less than 15% of the clear aperture of an amplifier because the beam intensity falls off slowly with distance from the axis. Truncating the Gaussian with a hard aperture as shown in Figure 4 creates a near ideal profile, but one that will not propagate. Diffraction from the sharp corners on the truncated profile creates large amplitude, high frequency spatial modulation. Spatial filters control the diffraction by eliminating the high spatial frequencies and by reimaging the profile at a relay plane down beam from the spatial filter. The resulting profile is a compromise between aperture utilization and propagation.[2]

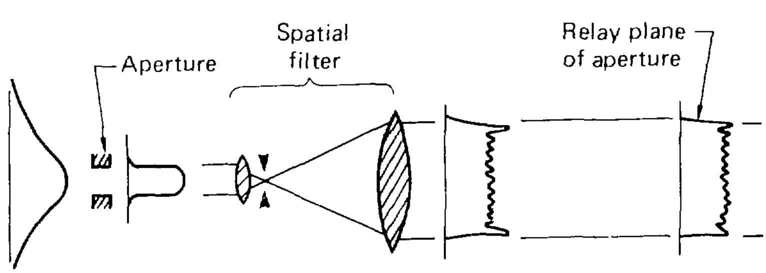

Fig. 4 - Shaping and control of the transverse beam profile.

Prepulse energy, energy which arrives at the target ahead of the main pulse, must not exceed a few millijoules to prevent premature damage to fusion targets. Nova has a net small signal gain of 10^{13} between the oscillator system and the target. Consequently, extremely low levels of prepulse energy injected by the oscillator system or the MOR amplifiers can threaten the targets. Unwanted portions of the oscillator waveform are attenuated by fast optical shutters in the oscillator system and after each 1.0 cm rod amplifier, giving a total discrimination of 10^{12}. Amplified spontaneous emission (ASE) from the first four MOR amplifiers is strongly attenuated by a diffraction limited spatial filter and by the beam forming aperture. Additional discrimination from an optical shutter at the MOR output makes the total ASE from the MOR less than from the amplifier chains.

Figure 5 shows the MOR layout. The oscillator system is located on the central table near the control console. The preamp table stands away from the wall allowing access to components from both sides of the table for easy maintenance. The two alignment packages hold the preamp alignment to fixed pointing and centering references. Separate control loops for the two oscillator systems, for the two injection locations of the CW alignment laser, for the bypass beam line around the 5.0 cm rod amplifiers, and for the synchronization system allow any one to be automatically aligned to the preamp beamline.

The layout also allows room for future expansion. The actual components are considerably narrower than the schematic representation in Figure 5. Enough space exists for an additional oscillator system and preamp to provide a diagnostic pulse capability. There is also space on the central table for temporal pulse shaping hardware.

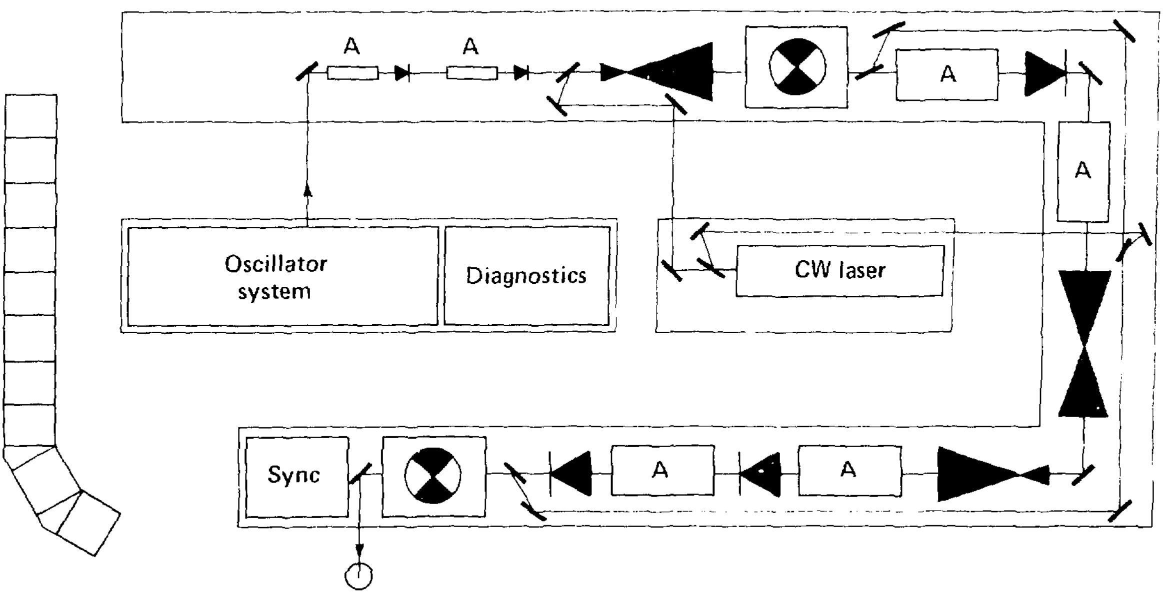

Fig. 5 - Master Oscillator room layout.

Splitter Array

The splitter array divides and transports the MOR output to each of the 20 individual amplifier chains. Four additional 5.0 cm rod amplifiers are also included, one each after the first four splits. These reduce the damage threat to the MOR and SA optics when maximum drive is required. They are located on the ends of each of the four laser spaceframes as shown for one amplifier in Figure 6.

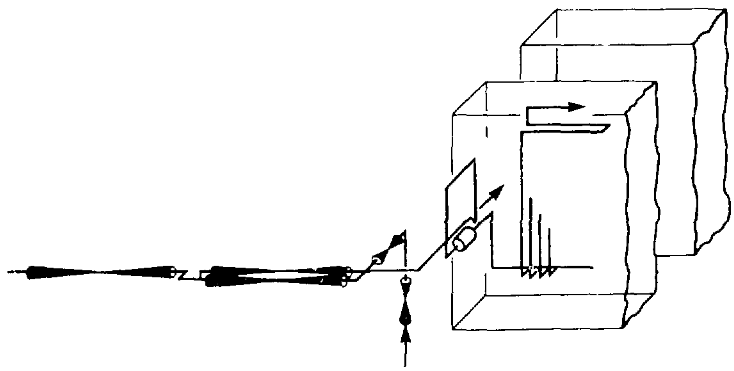

Fig. 6 - Splitter array schematic showing the five relays and one of the four rod amplifiers.

A total of five relays preserve the spatial profile from the MOR over the 60 meter propagation path to the chain inputs. The relays are located as early as possible in the splitter array to avoid duplication of relays after each split.

Each division of the pulse is done with an adjustable, computer controlled beam splitter as in the MOR. Adjustability allows the distribution of input pulse energies for the chains to be modified without loss of total pulse energy.

The last 5-way split on each of the 4 spaceframes occurs near the floor level for easy access. Each of the arms requires a "trombone" segment to allow relative adjustment of the pulse arrival times at the target. These are provided after the last split and before the chain inputs as shown for one beamline in Figure 6. The trombone sections are oriented horizontally and the two vertical beam segments are off-set accordingly.

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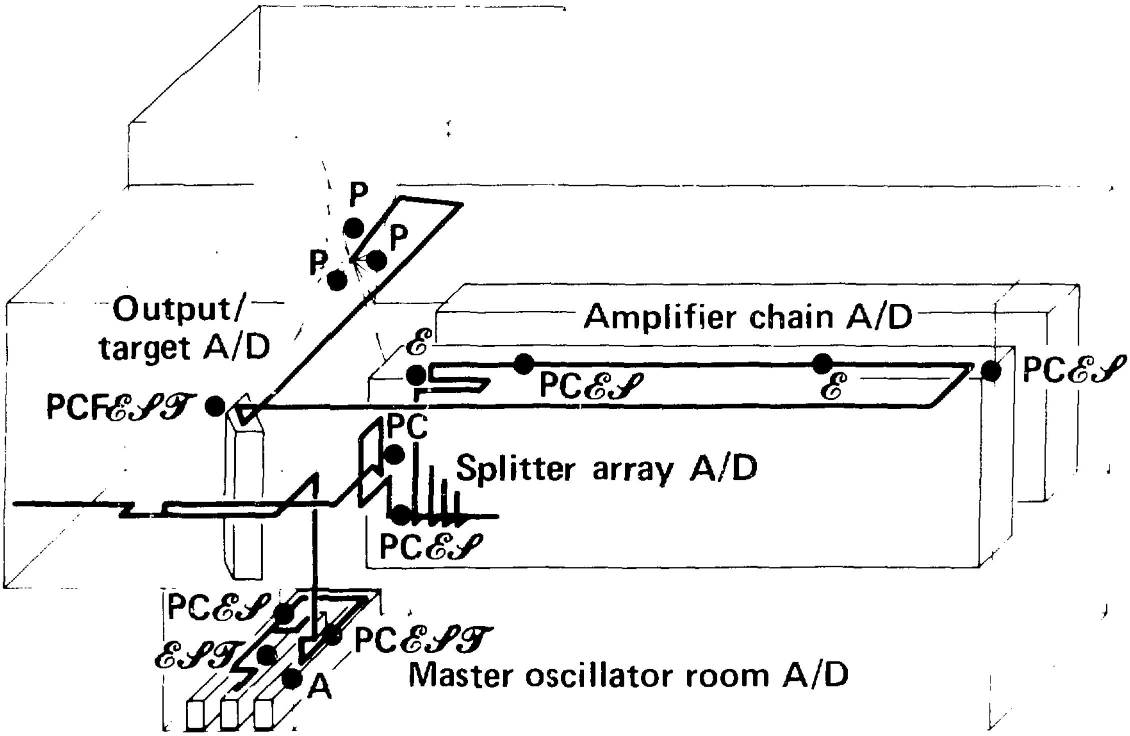
7. NOVA ALIGNMENT AND LASER DIAGNOSTICS SYSTEMS

The alignment and laser diagnostic systems guide laser pulses through the separate amplifier chains to the target, measure their temporal, spatial, and energy characteristics, and ensure simultaneous arrival at the target to within 5 picoseconds. Alignment tasks accomplished prior to each target shot involve automatic or remote-manual adjustments of approximately 2000 stepper motors and other actuators for the full 20 beam, 3 wavelength system. At the time of a target shot over 200 energy values are measured simultaneously. The sensor packages and individual detectors used for gathering alignment and diagnostic data are modular to minimize the number of different design and fabrication efforts. The output sensor, for example, comprises separate, but essentially identical, modules for each of the three operating wavelengths. The primary detectors for alignment functions are CCD cameras with both digital and standard video output. Automatic alignment loops are closed by digital processing of the video data. At the same time, an operator can easily monitor the automatic operation by viewing standard video displays. The primary detectors for diagnostic instrumentation are absorbing glass calorimeters, calibrated photodiodes, and photographic film. High speed streak cameras also play an important role. Diagnostic instrumentation of such a large optically pumped laser is particularly challenging, because both the optical and electromagnetic background levels at shot time are very high. Diagnostic data handling and processing is accomplished digitally, and both the alignment and diagnostic systems are integrated into the facility-wide digital control network.

System Overview

Alignment and laser diagnostics tasks for Nova are performed by the four major subsystems identified in Fig. 1. These subsystems are located in different parts of the facility, and they sample beams of widely varying diameter and signal level. However, the same basic functions are performed in each area, as noted in the figure.



Alignment functions
- A — Pulse arrival synchronization
- P — Beam pointing/target or pinhole viewing
- C — Beam centering/near field viewing
- F — Beam focusing

Diagnostic functions
- ℰ — Calorimetry
- 𝒮 — Spatial profile measurement
- 𝒯 — Temporal profile measurement

Fig. 1 - Alignment and laser diagnostic subsystems, sensor locations (C), and sensor functions for a single amplifier chain in the East laser bay.

(a) (b)

Fig. 2 - (a) Retracted centering reference cross hair (b) Inserted cross hair.

At a number of locations the position of the beam is compared with insertable cross hair references which are mounted permanently on the system's supporting structure. Such comparisons are made by examining a near field image of the beam in the plane of each cross hair on which the beam should be centered and this function is designated by a "C" in the figure for each sensor with near field viewing capability. More than one cross hair can be viewed by most sensors, and there are 8 cross hair locations in each chain. Centering accuracy requirements are typically 1% of the beam diameter. The photographs in Fig. 2 show a small aperture cross hair mechanism in the retracted and inserted positions. This device and larger ones of similar design are stepper motor driven and are controlled through the Nova digital control network.

At most sensor locations the precise propagation direction of the beam is also important. In the MOR and Splitter Array, for example, each of the principal beam path segments is defined as the line which passes through the center of a particular cross hair pointed in a specified direction. A sensor package in each path provides the ability to monitor pointing, as designated by a "P" in the figure. The sensor brings the beam to a focus on the detector, and offsets of the beam at this focus are proportional to pointing angle changes. Pointing accuracy requirements range from $\pm$ 15 μrad in the MOR to $\pm$ 4 μrad in pointing the output beam at the target.

In the pointing mode of operation the sensors are being used as far field viewers and can also provide images of spatial filter pinholes and/or the target depending on their location in the system.

Pulse arrival synchronization is performed by a separate dedicated system described elsewhere[1], but the optical systems required to accomplish the centering and pointing measurements described above also provide much of the capability needed for beam focusing and for the important diagnostic functions listed in Fig. 1. This fact has led to the design of sensor packages which perform multiple alignment and diagnostic tasks. Several of these sensors are described below.

Major Sensors

Three sensor packages have been designed which address most of the alignment and diagnostic needs of the system. They are the Input Sensor, which is used in the Master Oscillator Room (MOR) and Splitter Array and near the input to each amplifier chain; the Mid-Chain Sensor, which monitors the beam at the point where it is folded back toward the output; and the Output Sensor[2] located in the Switchyard.

Input Sensor

Figure 3 is a schematic drawing of the Nova input sensor. This package is for sampling beams up to 5 cm in diameter to determine the beam's position relative to the insertable cross hair, measure its direction of progagation, measure the pulse energy at shot time, and record a near field spatial profile of the pulse beam on photographic film. Specific locations in the MOR, Splitter Array, and early part of the amplifier chain are shown in Fig. 1. The input sensors are mounted rigidly to the MOR tables and the laser bay spaceframes in order that they may be used as reliable long term references for system alignment.

The small fraction of the beam required for input sensor operation is reflected from dielectric coatings on the front surfaces of two Brewster angle beam splitters. Because of the Brewster angle orientation, the uncoated second surfaces of the splitters allow the remainder of the beam to continue on through the sensor. The path selection wheels in the center of the sensor and in front of the CCD camera head are stepper motor driven to predetermined positions to configure the sensor for each desired mode of operation.

It was a ground rule of the design that there be no moving parts in the beam path for the sensor's pointing mode. Therefore, the pointing mode path is straight through both wheels, and small errors in wheel rotation do not degrade the performance of the sensor as a pointing reference.

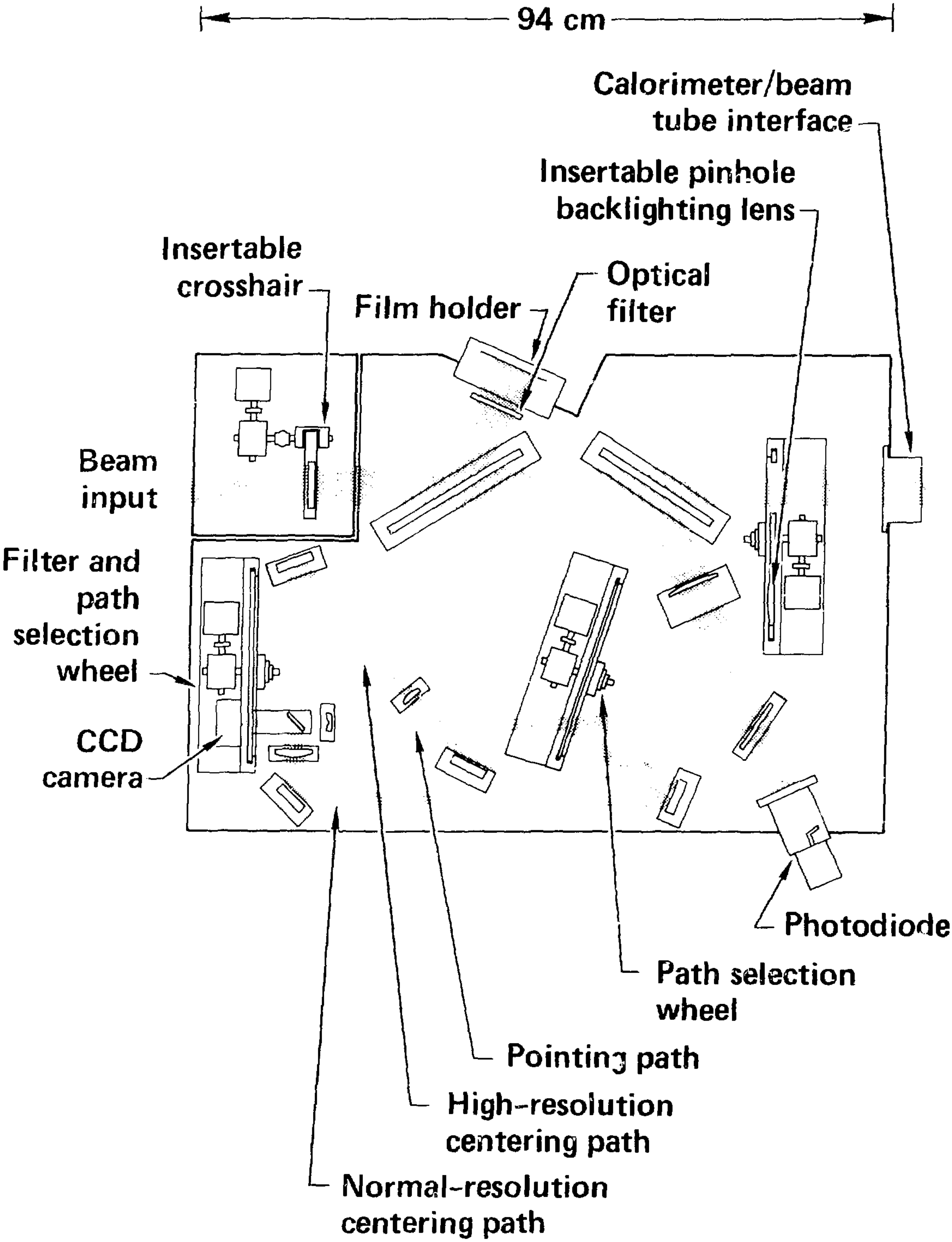


Fig. 3 - Schematic diagram of the Nova input sensor package.

Fig. 4 - Photograph of a Nova input sensor package. The various components may be identified by comparison with Fig. 3.

Figure 4 is a photograph of an input sensor with the cover removed so that all of the components are visible. The flat cable running out of the photo to the left connects the CCD camera head to its support electronics which are mounted separately for ease of maintenance and to keep heat sources away from other components. Figure 5 is a photograph of a camera electronics unit with its CCD camera head mounted behind a filter and mode selection wheel.

The images seen by the CCD cameras in the input sensors (and in other Nova sensors) are available to both the control system and the system operators over the system-wide TV network. A video digitizer converts the analog signals into a form which is suitable for use by the computers. Video analysis software then extracts alignment data from the image. Figure 6 shows an image which has been analyzed by a cross hair identification program. The black rectangle has been added to the picture by the computer to indicate that the center of the right-hand cross hair has been found by the program. The difference between the center points of the two cross hairs is used by the closed loop alignment program to calculate stepper motor commands for the gimbals which will correct the alignment error. Computer analysis of video data is an essential part of Nova closed loop alignment and is discussed more fully elsewhere.[3]

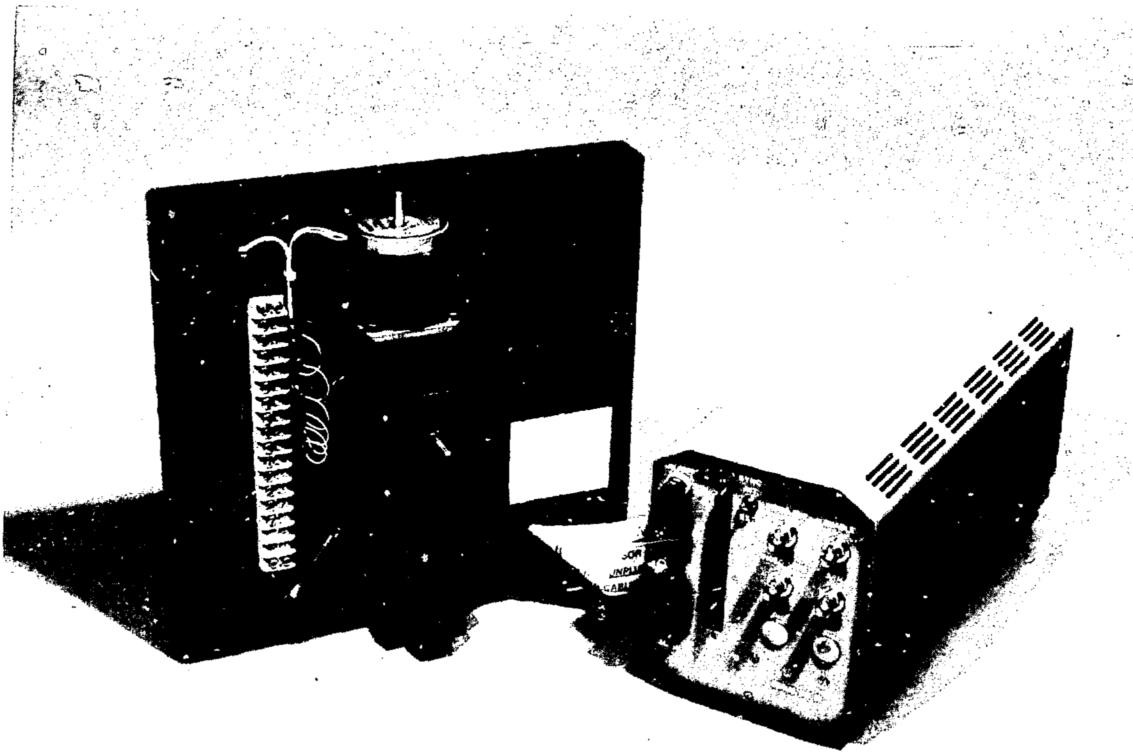


Fig. 5 - A CCD camera head and electronics unit. The header box measures 2 3/4" x 3" x 1 5/8" and is shown here mounted on the back side of a filter wheel.

Mid-Chain Sensor

The Nova mid-chain sensor is located at the point where the beam is folded back toward the chain output. Its capabilities are similar to the input sensor, but it has the additional flexibility of focus adjustment for both near and far field viewing. The hardware is actually a modification of an existing sensor package which will be removed from the Shiva laser system when it is deactivated. Figure 7 illustrates one of the functions of this sensor, providing images of spatial filter pinholes and the focused beam within each pinhole for those spatial filters ahead of the mid-chain location. Computer processing of these images followed by comparison of the center points for the pinhole and the beam results in stepper motor commands for centering the pinhole on the beam.

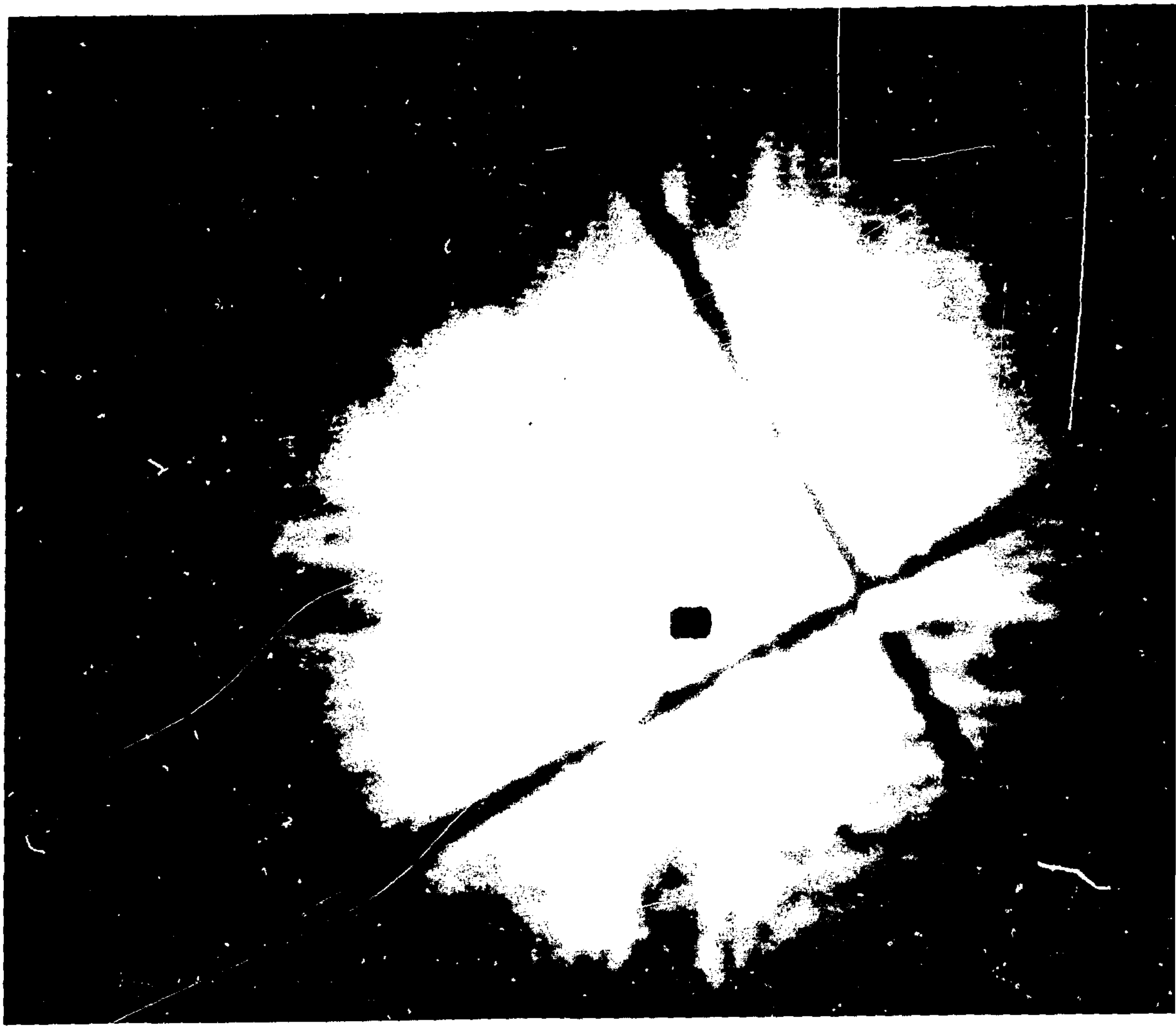
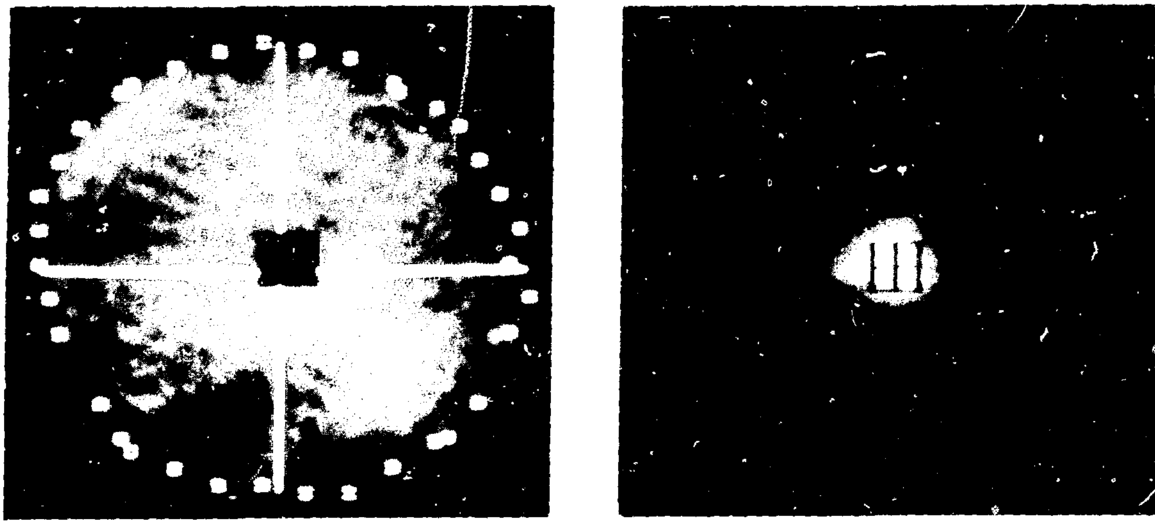


Fig. 6 - Cross hair images from a CCD camera after computer processing to locate the cross hair center indicated by .

Output Sensor and Related Components

The output/target alignment and diagnostics system is a prime example of multiple function design. Figure 8 identifies the components in this system. The output sensor, positioned behind a partially transmitting mirror, collects both alignment and diagnostic data from the laser directly as well as from the direction of the target.



(a) (b)

Fig. 7 - Video images used for spatial filter pinhole positioning. (a) Pinhole silhouetted against background illumination with computer generated edge markers and cross hairs. (b) Focused beam image with computer generated centroid indication.

Alignment to references which are closer to the target than the sensor poses the special problem that light must somehow be returned to the sensor. For centering the beam on the cross hair near the target chamber, light is reflected from an insertible mirror. For pointing the beam at a target, two approaches have been successfully demonstrated. The target can be silhouetted against the incoming beam with the signal continuing on across the target chamber and directed into the opposing sensor. Alternately, a reflective spherical surrogate target can be introduced in place of the fusion target, and the reflected beam will carry information about both the pointing and focus characteristics of the incoming beam back to the sensor.

Diagnostic measurements are also somewhat more complicated in the output system. For 1.05 μm (1ω) experiments the chain output is sampled on its way to the target, and light reflected from the target is directed into the sensor by the auxiliary mirror. Discrimination between these incident and reflected signals is accomplished by temporal gating to take advantage of the longer path traveled by the reflected light and by angle sensing using the auxiliary mirror to redirect the reflected beam by a specified amount.

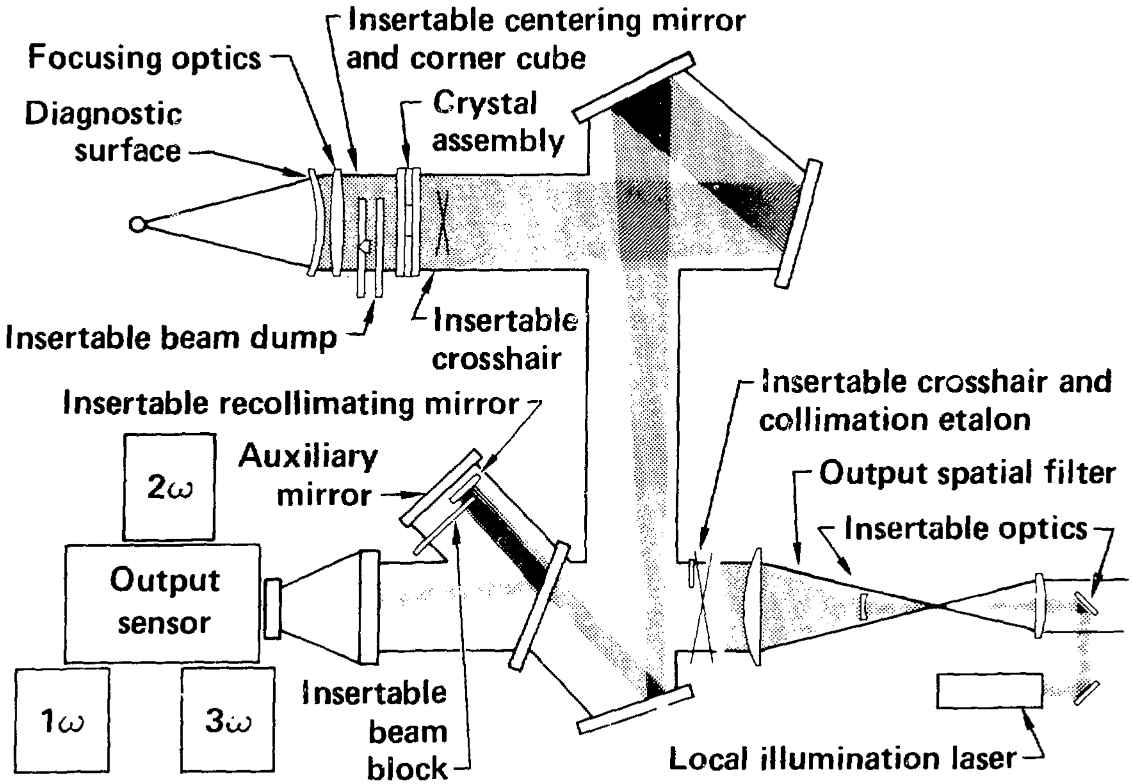


Fig. 8 - The output/target alignment and diagnostics subsystem. One set of shaded lines shows how a fraction of the light which has been frequency converted in the crystal assembly is returned to the output sensor. The other shaded lines illustrate the way in which a local source of frequency doubled or tripled light is used to obtain a full aperture alignment beam.

For experiments at shorter wavelengths the optical frequency of the output beam is doubled (2ω) or tripled (3ω) in an array of KDP crystals located just ahead of the focusing optics. Gimbal and lens adjustments for aligning the beam to the target are accomplished using a local source of 2ω or 3ω which is colinear with the 1ω beam. This local beam is inserted at the final spatial filter as shown in Fig. 8. Procedures for aligning the crystals to the beam are described in a companion paper.[4] To return a fraction of the 2ω or 3ω incident light to the output sensor for diagnostics, the final surface of the focusing optics is figured so that it reflects a slowly converging beam back toward the output sensor, as shown in Fig. 8. This splitter is tilted slightly so that, on reaching the first output turning mirror, the converging diagnostic reflection is offset from the center of the aperture and subtends only about 5% of the beam area. That fraction of the diagnostic beam which is transmitted by the turning mirror reflects off of a recollimating mirror in front of the auxiliary mirror and is directed back toward the output sensor.

The focusing optics diagnostic surface is so close to the target that the 2 or 3 incident light and the reflected light signals from the target arrive at the sensor within about 15 ns of each other, which is too close for temporal discrimination by the gating techniques used for 1 . Therefore, the target-reflected light and recollimated diagnostic beam must enter the sensor with enough of an angular difference to be completely separated spatially in the far field. The recollimating mirror repoints the incident diagnostics beam by the appropriate angle. Because of its offset and reduced diameter, this beam has an insignificant effect on the full aperture signals that also traverse the same path for other alignment and diagnostics functions.

Once the various incident and reflected beams have entered the output sensor, the signals are divided among three separate modules according to wavelength, as shown in Fig. 9.[5] Each module provides the capabilities listed in Table 1. Figure 10 serves to emphasize the point that this multiple function, multiple wavelength sensor is a large instrument.

Diagnostic Data Acquisition and Processing[6]

Data Network

Requirements for diagnostic-data acquisition and processing include rapid turnaround, effective interfacing with the alignment and power-conditioning controls, preservation of data under failure conditions, options for local or control-room modes of operation, and portability of the hardware required for off-line troubleshooting and calibration. In addition, the system must be able to operate in an environment characterized by significant electromagnetic interference at shot time when the tens of megajoules stored in the capacitor bank are discharged into the amplifier flashlamps. Figure 11 shows the major elements of a digital system which meets these requirements. A further potential difficulty, operating in the presence of prompt radiation from the target, has been avoided by locating all laser diagnostic components outside of the target room.

Diagnostic signals are generated by streak cameras, photodiodes, and calorimeters and collected in one of two ways. In the first instance, single detectors that produce large blocks of data, such as CCD readouts for streak cameras (160K words) interface directly to the fiber-optic communications bus (Novanet) and data is transferred directly to the top-level Nova computers, VAX 11/780's located in the control room. Data from transient digitizers are also handled by direct interface to Novanet and subsequent processing by the control room computers. These computers have enough memory and speed to process the large volumes of data or generate the complex displays associated with time resolved signals.

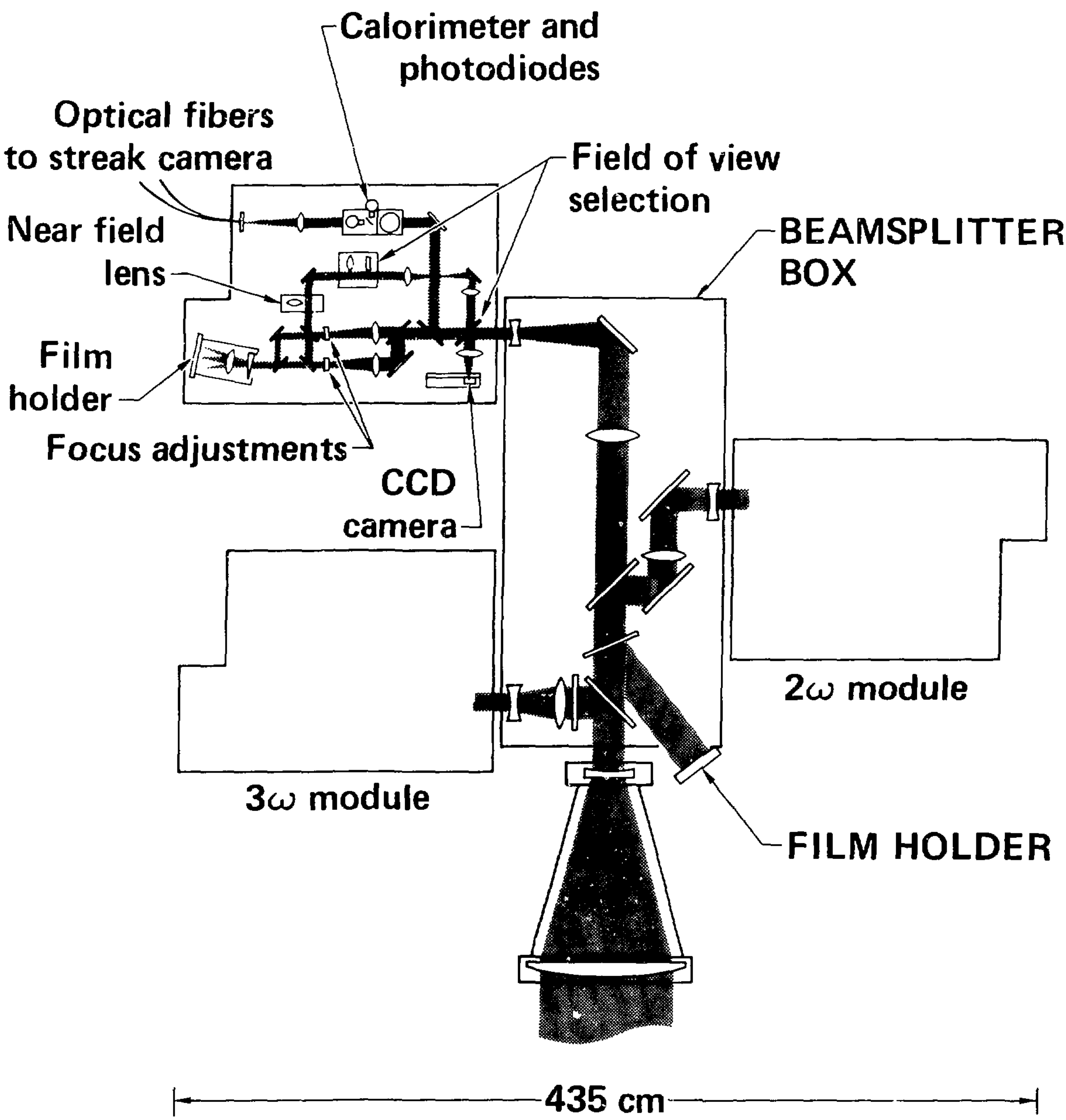


Fig. 9 - The design of the output sensor is modular by wavelength. The 1ω, 2ω, and 3ω modules are mechanically and optically as similar as possible. This figure shows some detail for the 1ω module only.

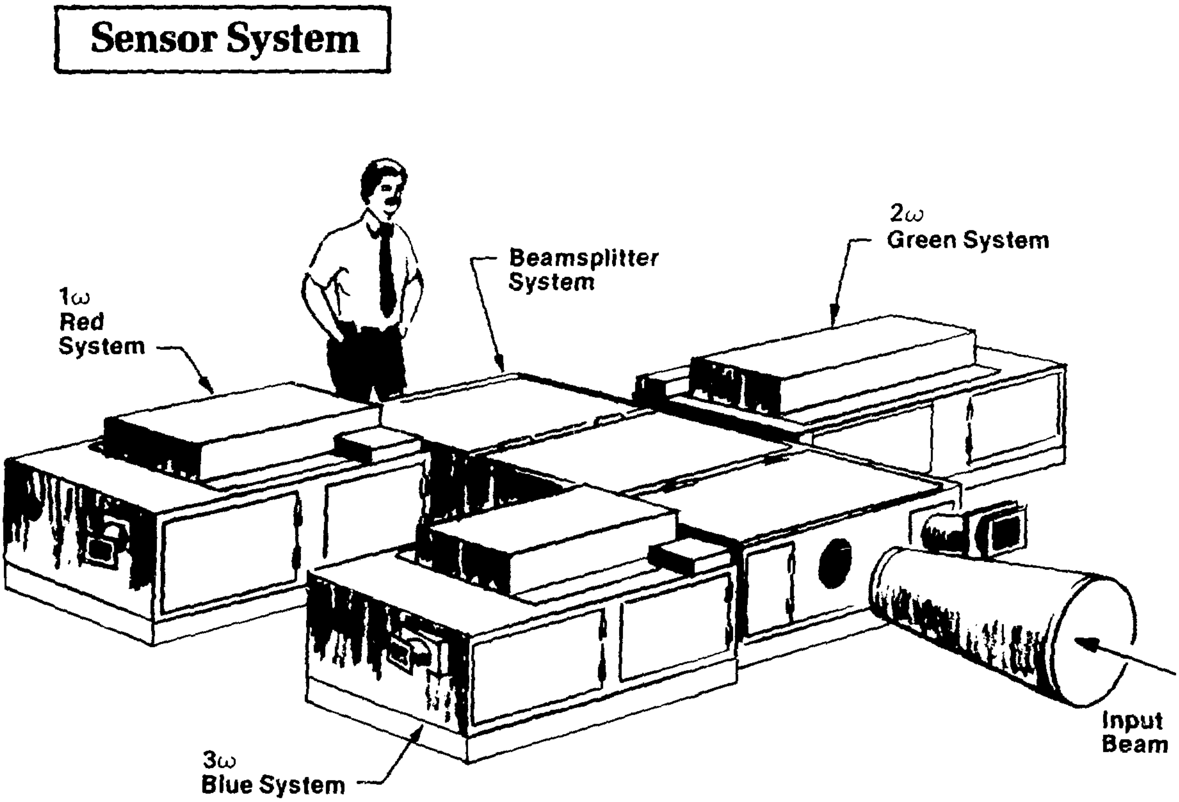


Fig. 10 - Artist's sketch of the Nova output alignment and diagnostics sensor.

In the second instance, for a diagnostic task that produces a small quantity of data per detector (e.g., calorimetry) but that requires many such detectors, groups of detectors are connected to a microprocessor located near the detectors. This front-end processor (FEP) collects the data and supplies control signals for the detector electronics. Operator interface at this level is through a control panel on each microprocessor chassis. Figure 12 is a photograph of an LSI-11 FEP with the laser diagnostic control panel. Similar FEPs with different control panels are used for the lowest level of control of all the stepper motor driven devices in the laser system and for local control of the power conditioning system.

These FEPs are interfaced to each other and to the top level computers in the control room via the Novanet fiber-optic bus and a multiported shared memory. The shared memory thus provides interconnection between the alignment diagnostics, and power conditioning controls. With this network configuration[3] the mechanical functions shared by alignment and diagnostics can be readily controlled by either laser diagnostics or laser alignment software.

Table 1. Output Sensor Capabilities (Except where noted, performance is the same for all wavelengths).

Calorimetry measurements

- Total energy entering target chamber focusing lens.
- Energy reaching target plane within a specific diameter (four choices of diameter), i.e., focusable energy.
- Energy reflected from target back through target chamber focusing lens.

Near-field imaging

- Standard TV format for three fields of view (20, 45, and 100 cm) with 425 m total focus range (300 m for 2ω and 3ω).
- Photograph of beam in plane approximately equivalent to focusing lens plane (1ω only).

Far-field or target-plane imaging

- Standard TV format for four 1ω fields of view (0.20, 0.45, 1.00, and 5.00 mrad) with 30mm total focus range relative to focus of the target chamber focusing lends.
- Standard TV format for three 2ω and 3ω fields of view (0.11, 0.25, 1.25 mrad).
- Multiple exposure level photographs of target plane taken with reflected light and of equivalent plane using incident light.

Miscellaneous

- Operates in preshot alignment mode with as little as 10 W cw power to the sensor, and in a shot diagnostic mode with up to 700 J.
- Auxiliary outputs for streak-camera, prepulse-monitor, or interferometer modules.
- All operating mode changes and adjustments are stepper motor driven.

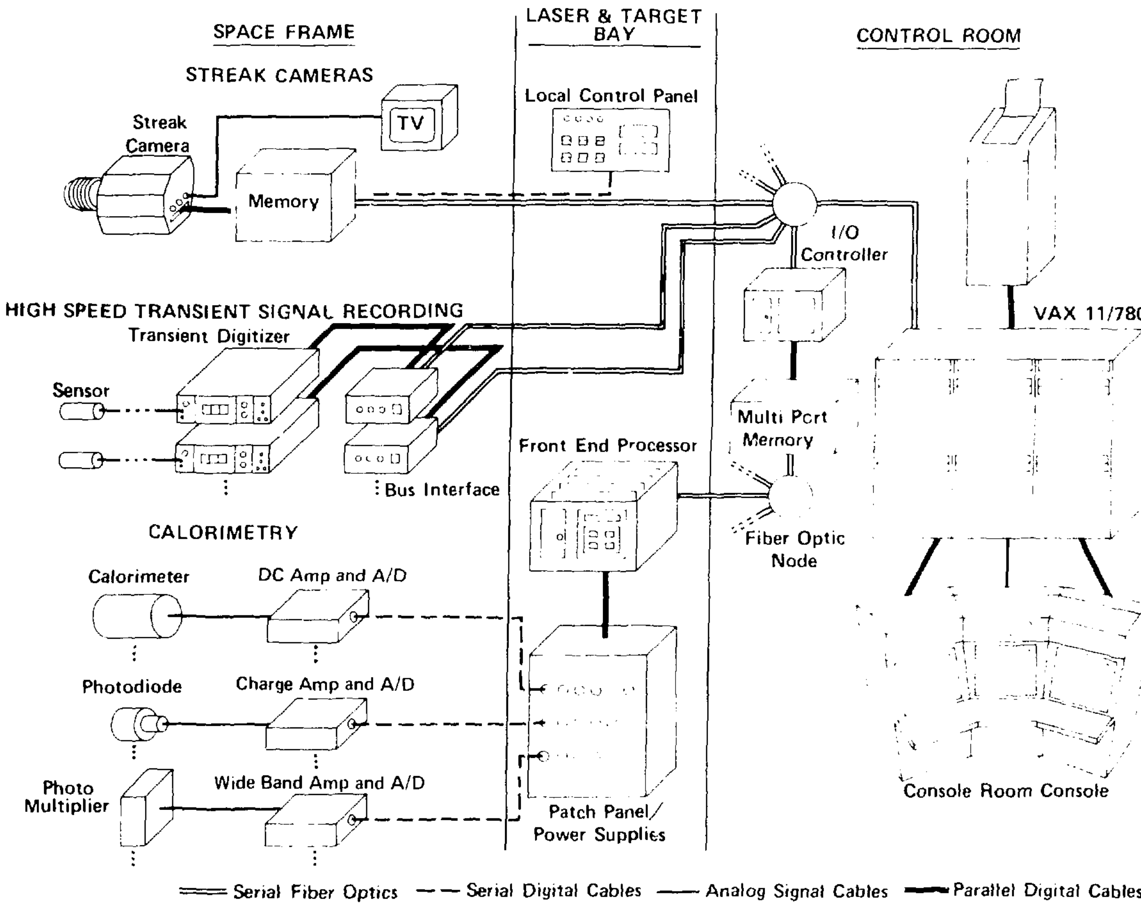


Fig. 11 - Major elements of the diagnostics data-acquisition and processing system. This system will control the status of diagnostic electronics, collect raw data from individual detectors, and perform all the analyses necessary to provide useful diagnostic information for laser operation.

Trigger Network

There are three types of triggers for laser diagnostics on Nova: high-speed triggers, with less than 1 ns jitter and resolution; medium-speed triggers, with less than 100 ns jitter and resolution; and low-speed triggers, with approximately 1 μs resolution and 200 ns jitter. These triggers form an interlaced network to control the operation of all laser diagnostic devices.

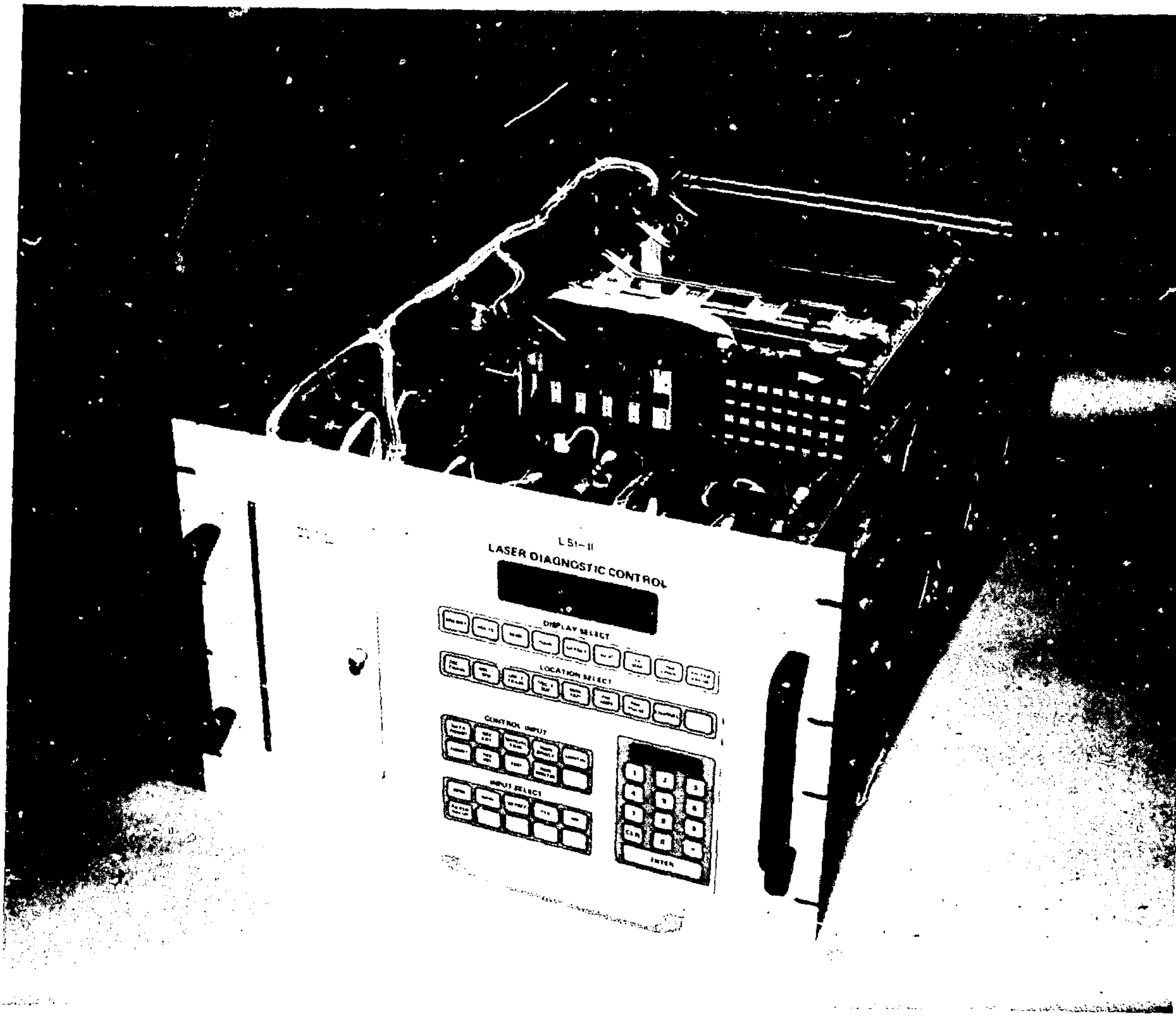


Fig. 12 - Laser diagnostic LSI-11 microprocessor chassis.

The high-speed triggers originate directly from the countdown circuitry for the Q switch of the oscillator. During a period that extends for several milliseconds before Q switch time, a time can be selected with 1 ns precision relative to the actual Q switch time. This time selection allows detectors to be triggered at precise times with respect to the arrival of the optical pulse. The high-speed trigger is used with streak cameras and transient digitizers to start the sweep before the optical signal arrives.

The medium-speed triggers, which also originate at the oscillator, are required throughout the laser bay, oscillator room, and switchyard to control a gate circuit in the photodiode charge amplifiers. A gate of approximately 1 μs is used to discriminate the laser pulse from flashlamp light. These triggers originate from a few oscillator timing channels; each pulse is then regenerated and fanned out in parallel to a number of charge amplifier locations.

The low-speed triggers are generated by the power-conditioning system through programmed timing channels on the power-conditioning bus, Novabus. These signals are used to trigger the FEPs to notify them of a shot.

All triggers are transmitted over fiber-optic cables. This mode of transmission provides complete electrical isolation between source and destination. In the case of triggers originating from the oscillator, this isolation is essential so that noise is not transmitted back to the oscillator timing circuitry. Noise picked up along wire cables might also disrupt the gate timing of the charge amplifiers.

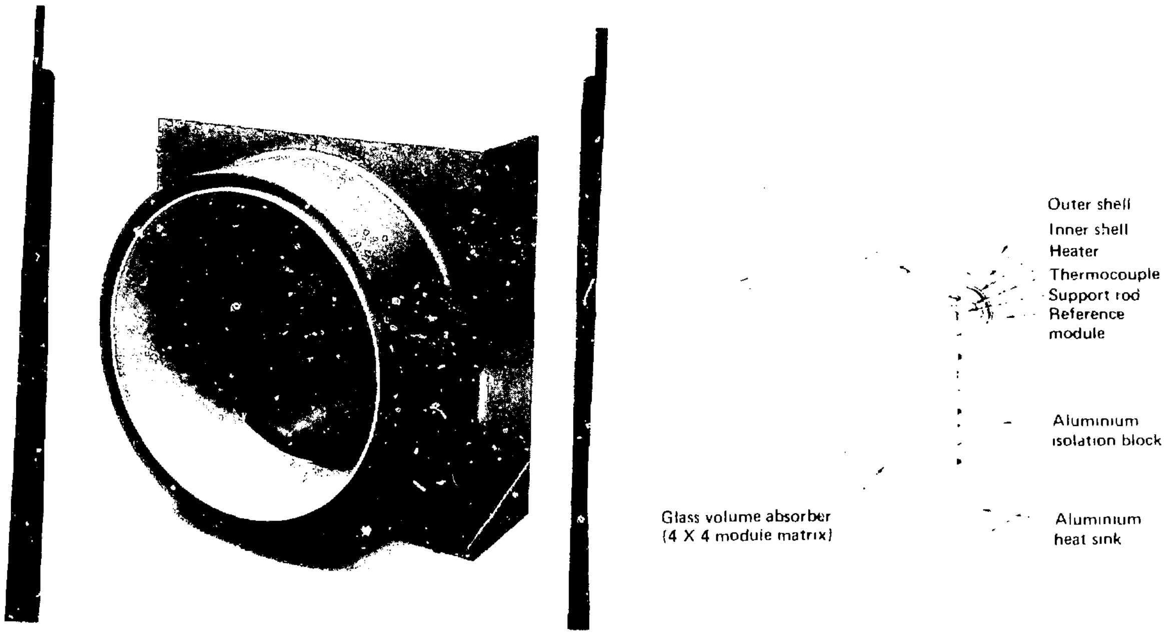
Calibration for Calorimetry

Laser energy measurements in Nova are made with photodiode calorimeters or absorbing glass calorimeters. The input sensor, for example, uses a photodiode as indicated in Fig. 3. In each case, the calorimeter sees only a small fraction of the energy which is in the main beam at that point. Accurate energy measurements are dependent on precise determination of the scale factor between the sensor calorimeter and the main beam energy. At the input sensor, provision has been made to insert an absolutely calibrated absorbing glass calorimeter in place of the beam tube at the sensor output for this purpose (see Fig. 3).

As the beam diameter and the energy per laser pulse increase toward the output of the amplifier chain, this calibration process becomes increasingly difficult. Previous calorimeter designs fail because of excessive equilibration time if they are simply scaled to an 80 cm clear aperture, for example. Furthermore, the requirement to measure 10 to 20 kJ pulses at multiple wavelengths severly limits the choice of absorbing material. Nova large aperture volume absorbing glass calorimeters utilize a matrix construction illustrated in Fig. 13.[8] Equilibration time for such calorimeters is characteristic of the individual matrix element dimensions rather than the full aperture dimension. The absorbing glass (Schott NG-4) is 3 mm thick and is chosen with due regard for laser induced damage properties and flourescence radiation losses. This calorimeter and others used for sensor calibration are themselves absolutely calibrated using an electrical resistance heater.

Concluding Remarks

At Lawrence Livermore National Laboratory the transition from manual laser alignment and hand processing of raw diagnostic data to automatic closed loop alignment and automated data acquisition and processing began in earnest on the Shiva laser, which became operational in 1978.[9] That transition continues on Nova. Key improvements include increased monitoring capability for the operator in the form of TV images for all alignment tasks, multiple function sensor design in which several alignment and laser diagnostic tasks are performed by a common sensor package, and expanded use of fiber optic links for noise immune transmission of both control signals and data.



(a) (b)

Fig. 13 (a) Prototype 34 cm aperture absorbing glass calorimeter. (b) Schematic diagram showing the segmented absorber and shared ambient reference module.

The Nova alignment and laser diagnostic systems incorporate the lessons learned during operation of Shiva as well as new ideas which have appeared with the passage of time and improvements in technology. A number of people have contributed to this process in addition to the authors of this paper. They include B. V. Beeman, D. M. Benzel, J. A. Prior, G. F. Ross, and J. D. Wintemute of Lawrence Livermore National Laboratory; B. W. Little, J. R. Grime, F. J. D'Amore, O. S. Demeter, G. L. McCrobie, R. P. Murray, D. A. Selling, and V. B. Zirkelbach of Aerojet Electrosystems Company; W. J. Nolan and R. O. Hutchinson of Kaiser Engineers Incorporated; J. L. Wilkerson, D. A. Cloyne, and R. L. Saunders of Bendix Field Engineering Corporation; and E. D. West of Calorimetrics Incorporated.

References & Footnotes

1. Nova uses the synchronization system developed for use on Shiva by Hughes Aircraft Company under contract to LLNL. See B. H. Mueller and S. Sheldrake, "Pulse Synchronization System, "IEEE/OSA Conf. Laser Eng. Applications, Tech. Dig., Paper 11.9, 1977.

2. Laser Program Ann. Rep., 1980; Lawrence Livermore National Laboratory, Rep. UCRL-50021-79, section 2, 1981.

3. G. J. Suski et al., "The Nova Control System - Goals, Architecture, and Central System Design," Chatper 11.

4. M. A. Summers et al., "Nova Frequency Conversion System," Chapter 8.

5. Work on the conceptual design of the output sensor and the detailed design and prototyping of the 1 and 2 modules was performed at Aerojet Electrosystems Company under contract to LLNL.

6. R. G. Ozarski, "Laser Diagnostics for a Multi-wavelength Laser Fusion Facility," Laser Focus, December 1981.

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8. Work on the design and prototyping of large aperture calorimeters was performed at Calorimetrics Incorporated under contract to LLNL.

9. D. R. Speck et al., "The Shiva Laser - Fusion Facility," IEEE J. Quantum Electron., vol QE-17, pp 1599-1619.

8. NOVA FREQUENCY CONVERSION SYSTEM

Frequency conversion of Nd:glass lasers by harmonic generation is routinely used for generating intense visible and ultraviolet light. In this article, we describe our plans for implementation of harmonic generation on the Nova laser. The basic concept, scaling to large aperture and integration with the alignment and diagnostic systems are discussed. In addition, the multi-wavelength target focusing system is described.

During the past three years, low energy, plasma physics experiments at LLNL and other laboratories around the world have supported theoretical predictions of significantly improved laser fusion target performance using shorter laser wavelengths. High energy target implosion experiments, which more closely match actual high gain fusion target conditions, are being planned to verify estimates of target yield and to characterize target performance versus wavelength.

The most expeditious and cost effective approach to realizing a short wavelength target irradiation capability of appropriate scale is to frequency convert an existing Nd:glass laser facility. Harmonic generation technology based on nonlinear optical interactions in anisotropic crystals makes this possible.

In anticipation of formal approval to proceed with frequency conversion of the Nova laser, we have prepared a baseline design which will provide the capability to operate Nova at the fundamental (λ_{ω}= 1.053 μm), second harmonic ($\lambda_{2\omega}$ = 0.527 μm) and third harmonic ($\lambda_{3\omega}$ = 0.351 μm) wavelengths.

Basic Concept

The first harmonic generation experiment was performed by Franken et al.[1] in 1961 shortly after the invention of the laser. In this experiment, a ruby laser pulse (λ = .6943 μm) was focused into a quartz crystal. An extremely small fraction (10^{-8}) of the incident energy was detected at the second harmonic (λ = .3472 μm). In the following year, Giordmaine[2] and Maker et al.[3] devised an ingenious and now widely used phase-matching technique employing the birefringence of unaxial crystalline materials to significantly increase the conversion efficiency. Fifty to seventy percent conversion of the fundamental to the second harmonic is common at fundamental intensities in the GW/cm^2 range.

Let us outline a simple picture of this process. When a low intensity light wave propagates through a transparent medium, as shown in Fig. 1, its oscillating electric field drives the electron cloud of the constituent atoms. These oscillating electric charges constitute a polarization wave which gives rise to a radiated wave. Since the oscillatory motion of the electrons follows the driving field, this radiated wave is of the same frequency as the incident wave representing the usual "linear" response to the light. The wave emerges from the transparent medium with its frequency unchanged, but with a phase delay which we attribute to the refractive index of the materal.

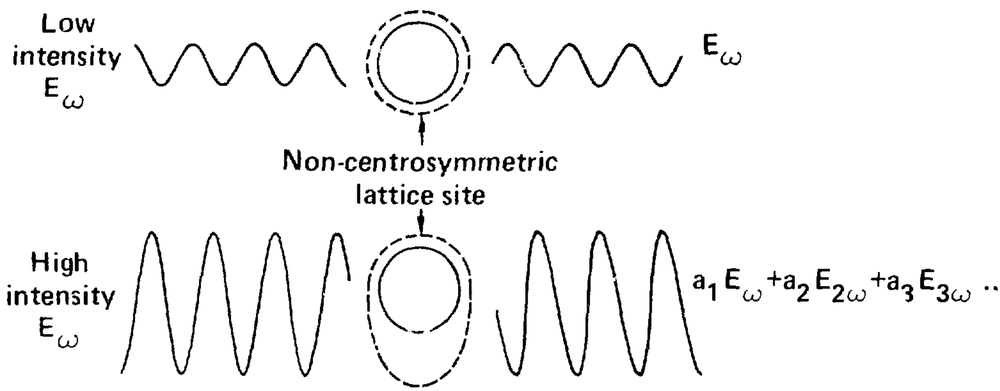

Fig. 1 - Origin of the harmonic wavelengths.

Laser pulses typically have a spectral brightness - power density per steradian-Hz which is many orders-of-magnitude greater than that of incoherent sources. It is this property which enables the laser pulse to cause a more vigorous oscillation of the electron cloud. The excursion of the electrons about their "resting" positions may easily be 100 times larger than the truly minute excursion induced at low intensity. Consequently, the electrons probe the repulsive potential presented by neighboring atoms to a greater extent. It is this condition which allows the material structure to influence the frequencies of light that are to be radiated by the oscillating electrons. When the strength of the repulsion in a particular direction is not the same in the opposite direction, the electron motion will be biased by this asymmetry. The radiated wave will be distorted, i.e. contains harmonics of the fundamental, representing the "nonlinear" material response to the light.

Let us consider second harmonic generation. Each wavelet at the second-harmonic frequency radiates outward at the phase velocity of the medium for $\lambda_{2\omega}$, which is the vacuum light speed divided by the refractive index at $\lambda_{2\omega}$. However, the fundamental wave propagates with a different phase velocity, determined by the index of refraction at λ_{ω}. Because it is the fundamental wave which instills the phase on each of the electron oscillators, and thus on the radiated $\lambda_{2\omega}$ wavelets, the net radiated wave at $\lambda_{2\omega}$ is the sum of many out-of-phase wavelets from the host of oscillators throughout the material. The result is very low conversion of the laser energy from the fundamental to the desired wavelength $\lambda_{2\omega}$. We say the process is not phase-matched.

To achieve the phase-matching condition so that the $\lambda_{2\omega}$ wavelets will add coherently, we must arrange for the phase velocity of the fundamental wave to equal that of the second-harmonic wave. This is usually accomplished by choosing a material with anisotropic characteristics which can be used to compensate for the dispersion. The wavelets from all the oscillators will then reinforce each other and result in a high conversion efficiency.

The first material to exhibit phase-matched second harmonic generation was KDP (KH_2PO_4).[2] Although the number of candidate materials has climbed into the hundreds, KDP remains the best choice for the frequency conversion of the Nova laser. The refractive index dispersion curves for a negative uniaxial crystal, eg. KDP, are shown in Fig. 2.

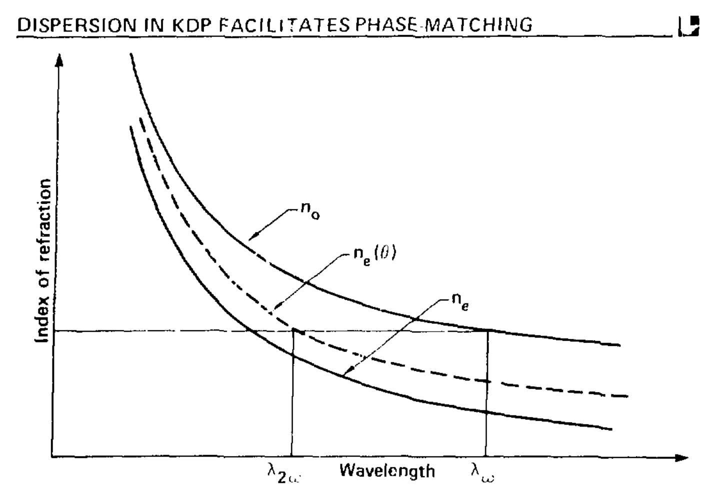

Fig. 2 - Phase-matching is achieved by using anisotropic crystals.

Light polarized perpendicular to the crystal optics axis propagates with a phase velocity determined by the "ordinary" index of refraction n_o. The orthogonal component propagates with a phase velocity determined by the "extraordinary" index of refraction $n_e(\theta)$, which depends on the angle between the crystal optic axis and the direction of propagation θ. This angle can be adjusted by tilting the crystal about its ordinary axis (90° to the optic axis) until the phase-matching condition is achieved. Two types of phase-matching are possible:[4]

$$n^e_{2\omega} = n^o_{\omega} \qquad \text{Type I}$$

$$n^e_{2\omega} = \frac{n^o_{\omega} + n^e_{\omega}}{2} \qquad \text{Type II}$$

For clarity, TYPE I angle tuned phase-matching is illustrated in Fig. 2. although TYPE II will be used on Nova.

Baseline Design

Our objective is to convert the infrared (1.053 μm) light to visible (0.527 μm) or ultraviolet (0.351 μm). There are five major design requirements:

- High conversion efficiency from the fundamental to the second and third harmonics.
- Minimize nonlinear propagation effects.
- Harmonic generation at the 74 cm aperture.
- Integration with laser-target alignment and diagnostics systems.
- Multi-wavelength flexibility at minimum cost.

Conversion Efficiency

We have developed a system capable of producing the second and third harmonics over a wide range of input intensities, employing two identical crystal arrays.[5] Conventional approaches to this problem would require three different crystal assemblies, i.e. 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, 1.4 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. 3.

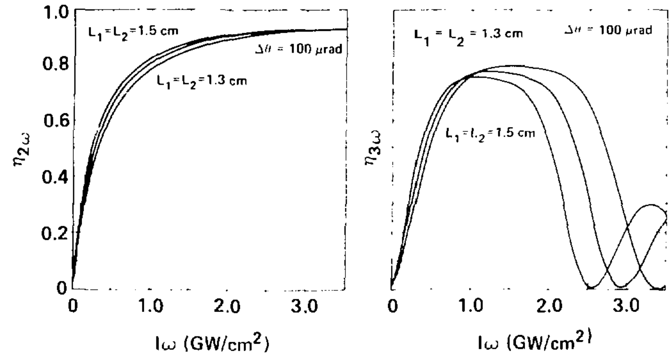

Fig. 3 - Second and third harmonic conversion efficiency for three crystal lengths calculated for flat, temporal and spatial profiles.

Third harmonic generation is easily achieved because the two crystal arrays are already in the basic orientation for the "Type II - Type II polarization mismatch" configuration.[6,7] Proper alignment is accomplished simply by rotating the assembly about the beam direction by 10° and angle tuning the second crystal (only one axis of the assembly) onto the mixer phase-matching angle ($\Delta\theta$ = 4.4 mrad). Efficient conversion is achieved over a somewhat smaller input fundamental intensity range than for second harmonic generation, but the design works best at the low intensity end of the Nova pulse width range, i.e., 2 - 5 ns. This operating range is consistent with other system constraints, i.e. nonlinear propagation effects.

This multi-wavelength capability is made possible by recognizing that the same two crystals used for the third harmonic can also be used for the second harmonic. High efficiency is achieved by opimizing the crystal lengths for the input intensity range of interest. Note that for commonality of parts, we have chosen both arrays to use identical crystal lengths. Our analysis indicates that this can be done with very little performance penalty.

Nonlinear Propagation

High power laser systems are limited in performance by intensity dependent propagation effects. At high intensity, the index of refraction of transmitting optics, e.g. laser disks, lenses, etc., is significantly modified by the presence of the intense laser beam

$$n = n_0 + \gamma I$$

where n_0 is the linear index of refraction, γ is the nonlinear refractive index coefficient, and I is the laser intensity. This behavior results in a spatially distributed intensity instability which is commonly called "self-focusing." An intense beam with weak spatial modulation, e.g. diffraction from dust, will become deeply modulated after propagation through the optical components. The resulting intensity spikes can damage dielectric coating and substrate materials. The modulation growth, in the "small signal" regime, is exponential with the intensity dependent phase retardation, B.[8]

$$B = \frac{2\pi}{\lambda} \int \gamma I d\ell$$

Our propagation analysis of the harmonic beam indicates that a maximum allowable B after the KDP crystal array is B < 2.5 radians. This is achievable only if some care has been taken to control diffraction from the gaps between crystals in the array, i.e. by apodization. This places a maximum value on the harmonic intensity that can propagate without damage through the remaining optics. The impact on system performance is shown in Fig. 4, assuming 20 cm of fused silica following the array. The lower maximum intensity at $\lambda_{3\omega}$ reflects our estimate of the dispersion in γ.

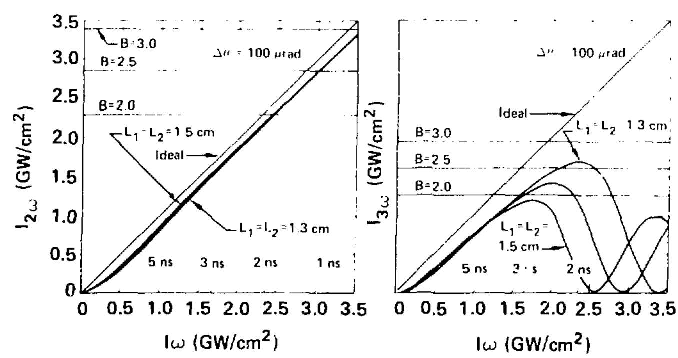

Fig. 4 - Second and third harmonic output intensity versus input for three crystal lengths. The maximum harmonic intensity is limited by B< 2.5. Note that the maximum Nova fundamental intensity as a function of pulsewidth is shown along the abscissa.

Large Aperture Arrays

Large aperture (74 cm) harmonic generation can be achieved in spite of limited single crystal size by using an array of small aperture crystals. We have employed this concept in the Nova design using two 3 x 3 crystal arrays in series, sandwiched between two antireflection coated windows. Three thin layers of index-matching fluid are used to reduce the Fresnel losses at surfaces inside the assembly. This composite array approach, shown in Fig. 5, is made possible by precisely machining the KDP crystals so that the phase-matching direction, i.e. beam direction, and surface normal are accurately aligned. Diamond turning technology and precise measurements of the phase-matching angle (± 30 μrad) have made this concept feasible.

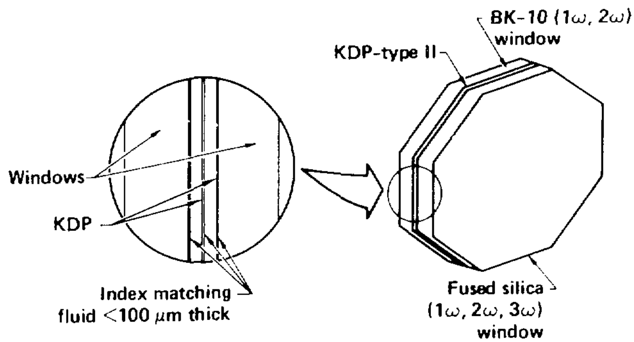

Fig. 5. - 3 x 3 crystal array assembly.

Requirements for optical quality of the beam place severe constraints on the mechanical design of the assembly. Two approaches have been developed and tested using a 15 cm clear aperture prototype assembly. The "egg crate" design employs a diamond turned, stainless steel lattice, in which the crystals are embedded, to accurately support the windows against an internal vacuum load. A "close packed" design in which the windows are pulled directly against the crystals has also been tested. The merits of each design are being evaluated.

It must be noted that a massive amount KDP is required for this project. The full Nova (20 beam) frequency conversion system requires 40 identical crystal arrays, i.e. 300, 27 x 27 x 1.4 cm crystal plates. Based on progress to date, we feel confident that the necessary large aperture KDP crystals will be available in time to meet the Nova activation schedule.

Alignment and Diagnostic Integration

After passing through the last spatial filter the infrared beam is imaged onto the target focus lens through a system of mirrors which are high reflectors for λ_{ω}. The frequency conversion will be accomplished after the last turning mirror and before the focus lens in each arm. The turning mirrors are also used to transport a diagnostic reflection at the harmonic wavelengths ($\lambda_{2\omega}$, $\lambda_{3\omega}$) back to the modular alignment/diagnostic sensor located behind the first turning mirror in an area shielded from electromagnetic interference and neutrons.

The alignment task can be viewed in two parts. First, alignment of the turning mirrors and focusing optics for the high power harmonic pulse to properly illuminate the target. Second, alignment of the crystal array onto the phase-matching direction for efficient harmonic conversion of the incident fundamental pulse.

The first part of the alignment task is accomplished by employing a local cw laser operating at the same wavelength as the desired harmonic of Nd:YLF. This local source is carefully aligned to be colinear with the system alignment laser, thereby providing a low power reference source of the desired wavelength. The turning mirrors and focusing optics can now be positioned using the standard target alignment techniques developed previously for operation without frequency conversion.

The second part of the alignment task is accomplished by using the master oscillator pulse train. When amplified by small aperture "high" repetition rate rod amplifiers (0.1 Hz) it is intense enough to allow alignment of the crystal array by maximizing the second harmonic conversion efficiency as monitored in the target chamber. However, this technique will not produce a measurable third harmonic signal. Consequently, alignment of the array for third harmonic generation is accomplished by an open loop alignment correction from the second harmonic position. This amounts to a 4.4 mrad tilt about one axis of the array.

To accurately diagnose the laser pulse incident on the target, a partial reflection from one of the components following the crystal array is directed back toward the alignment and diagnostic sensor package located about 30 meters away. This places an additional reflectivity requirement on the mirror coatings. However, high damage resistance and high reflectivity at $\lambda_{2\omega}$ and $\lambda_{3\omega}$ are not required because the reflected beam intensity is low (less than 4% of the harmonic intensity) and overly energetic for diagnostic purposes. This reflected harmonic signal will be used for calorimetry, spatial and temporal diagnostics.

Multi-Wavelength Flexibility

Minimizing the number of components requiring high power performance, at more than one wavelength, is the primary reason for locating the frequency conversion array just before the focusing optics. Typically, high power laser components achieve their best performance, e.g. damage threshold, reflectivity, wavefront distortion, when they are optimized for monochromatic operation. But, it is not economically feasible to require, for example, three sets of 74 cm aperture focusing optics, one for each wavelength. In addition, the total glass path at this location in the system must be minimized to permit high power operation. Recall that for constant B, beam intensity and glass thickness can be traded against one another. Therefore, the design of the frequency conversion and target focusing systems for multi-wavelength operation must be undertaken with the intention of minimizing the number of large aperture components required and their total thickness.

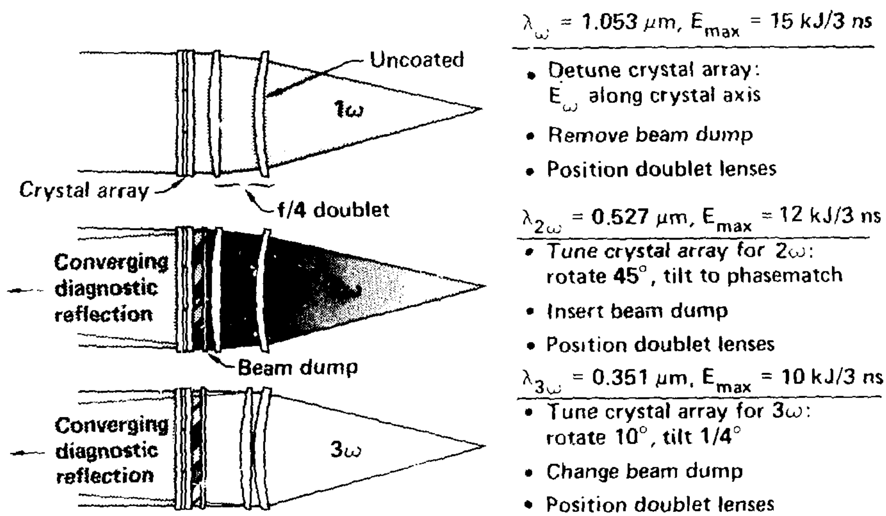

Fig. 6 - Schematic diagram of the Nova frequency conversion system and target focusing optics summarizing the multi-wavelength flexibility.

Our baseline design with this multi-wavelength flexibility is shown in Fig. 6. The crystal array described earlier has the capability of transmitting the fundamental or converting it to the second or third harmonic. It is assembled from fourteen identical KDP crystals 1.4 cm x 27 cm x 27 cm. The array windows are made of materials which transmit the desired wavelengths and are coated with broadband antireflection coatings based on the graded-index technology.[9] These window coatings, along with the index-matching fluid between the crystals and the windows, significantly reduce the optical insertion loss, i.e. Fresnel reflections in the assembly. Beam dumps are the only wavelength unique components in the system. They are used to absorb the undesired residual fundamental wavelength (λ_ω) or wavelengths (λ_ω, $\lambda_{2\omega}$).

The components which follow the array and dump must provide a vacuum barrier, a diagnostic reflection, and focus the light onto the target with a minimum of glass. The first element of the focus lens serves as a vacuum barrier and is an f/6 aspheric lens. The second element is an f/13 aplanatic lens with the last surface uncoated. The combination of these two lenses provides an f/4 focusing system with a 4% diagnostic reflection which can be focused to the alignment and diagnostic sensor. Changing the spacing between the two elements allows control of the convergence on the diagnostic reflection to accommodate arm-to-arm variations in the distance from the lens to the sensor. This spacing change also helps compensate for the focal shift in the target plane due to dispersion in the glass.

Concluding Remarks

The frequency conversion system described here will give Nova the capability of operating at the fundamental second and third harmonics with the flexibility to easily change wavelengths. High conversion efficiency can be achieved and nonlinear propagation effects accommodated over the intensity range of interest. Laser-target and alignment diagnostics requirements are accommodated at all three wavelengths without compromising the multi-wavelength flexibility.

The technical risks of such a large scale undertaking are rapidly being reduced and the laser fusion target performance payoffs are great. With the addition of this frequency conversion subsystem the Nova laser can provide a high energy, multi-wavelength target irradiation capability by the mid-1980's.

Dr. W. L. Smith's valuable contributions to this effort are greatly appreciated.

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9. NOVA TARGET SYSTEMS

This chapter includes descriptions of the target chamber, beam-focusing lenses and positioners, the target support and alignment structure, target diagnostics, and control of the radiation environment.

Target Room

We will locate the target chamber in a concrete-shielded room north of the laser bay and optical switchyard. Laser beams will be routed to the target chamber by a series of turning mirrors mounted on a steel spaceframe, as described in the paper by C. Hurley, et al.

During Phase I operation, we will irradiate the target with two 5 beam open cones, one each on the east and west ends of the target chamber. The included angle of the cone centerlines is 100°.

In Phase II, we will add 10 more beams in the west laser bay and reroute the existing beams so there will be no crossover between the east and west systems. Figure 1 shows the Phase II target chamber.

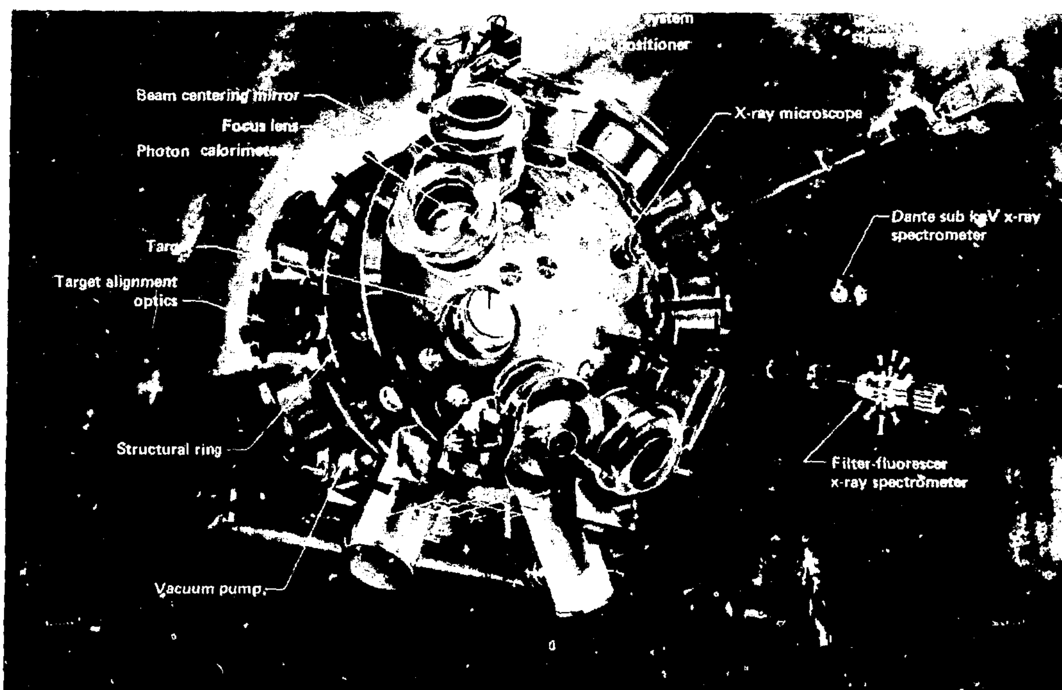

Fig. 1 - Nova target chamber, showing Phase II arrangement with 20 laser beams on 100° cone

Target Chamber

The target chamber will be supported 10 m above the floor, in the center of the target room. The main body of the chamber will have a 1 m wide central ring, with an inner radius of 2.13 m, to provide structural support for the target positioner, target-alignment optics, high-vacuum system, and target-diagnostics instruments.

We have designed two removable hemispherical heads, to be attached to the center ring, with ports for the laser beams, x-ray effects experiments, and target diagnostics.

Phase I requirements call for an experiment yielding 1 x 10^{17} neutrons from a 100 kJ, 1 ns laser pulse. The neutron, x-ray, and debris fluences generated by this neutron yield are not high enough to require local shielding or protection of the chamber by a first-wall absorber. Thus, the minimum radius of a hemisphere is dictated by mechanical considerations, primarily mounting of the focusing lenses. The baseline lens has a focal ratio of f/4.0 with a 740 mm clear aperture, but we are making provision for a future change to a lens with a focal ratio of about f/1.6. Because these faster lenses will, of necessity, have to be inside the target chamber, the ports in the hemispheres must be large enough to admit the full laser beam plus some mechanical hardware.

We have designed the target chamber for Phase II for laser energies of up to 300 kJ and for yields of up to 5 x 10^{18} n, with as much as 3.2 MJ of cold x-rays and 4.0 MJ of target debris. These conditions will require:

- A first wall for absorbing x-rays and debris
- An aluminum vessel to allow neutron-activated materials to decay rapidly to an acceptable level.
- A neutron shield around the chamber to limit activation of the steel spaceframe and concrete building.

To accommodate 10 lenses per side (instead of 5) and to reduce x-ray fluence on the first wall, the radius of the chamber must be a least 2.3 m.

We have conducted finite-element stress and deflection analyses, using the SAP IV code. Figure 2a shows the computer printout of the shell in the loaded condition. The dotted image shows the original, unloaded condition. Figure 2b is a section taken through a beam port and shows the deflections at various key locations.

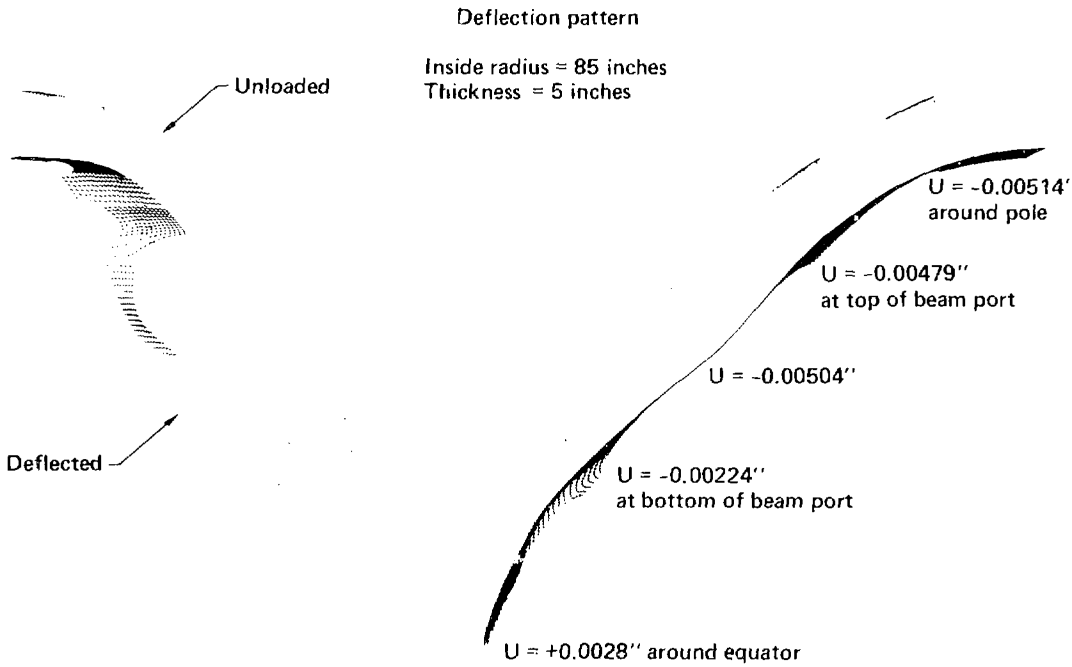

Fig. 2 - Computer printout of predicted deflections in an element of the Nova target chamber, using SAP IV finite element code

Vacuum System

The vacuum system will use mechanical pumps and Roots blowers for rough pumping and turbomolecular and cryogenic pumps for high vacuum pumping. We will attain a pressure of 10^{-5} Torr in 30 min and, ultimately, reach a base pressure of 10^{-7} Torr. An overall layout of the vacuum system is shown in Fig. 3.

The Nova vacuum controls are a graphics based closed-loop process control system. The vacuum system controls have been designed in keeping with all other control subsystems on the Nova laser, that is, centralized computer control with high speed communication (Novanet) to a distributed control front-end processor.

Control functions are entered on a touch panel and Ramtek color monitor which displays menus, submenus, and schematic drawings of the system and controlled items. Control commands are processed and distributed by a VAX 11/780 main computer and an LSI 11/23 local processor.

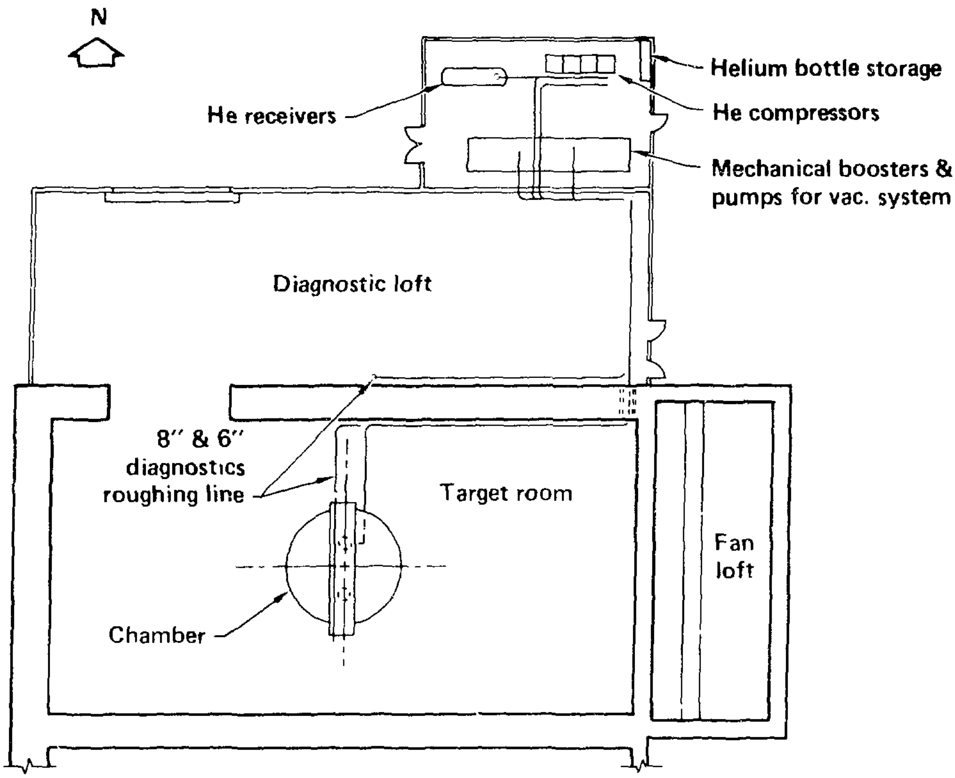

Fig. 3 - Nova vacuum system layout plan

The control system is able to handle up to 512 varied sensor input signals, both digital and analog. A maximum of 320 output lines are provided for control of valves, pumps, and status displays. Control and status are apportioned to polling and interrupt driven data acquisition methods. All sensor and pressure transducer values are displayed on another color monitor to provide a system functionality overview. Safety interlocks and legal/illegal valve state tables are also provided to protect personnel and delicate apparatus.

Overall system status, pressures, and states are displayed on a companion color monitor. Individual sensors and signal conditioning units operate at 100 khZ rate to achieve an overall system rate of approximately 250 updates and control commands per second. Operator functions are highly human engineered for ease of use and comfort over long periods of operation. English commands and mnemonics are used to enter system configurations and/or changes to the diagnostic subsystems.

Beam Focusing

One of the most difficult and exacting tasks associated with the target system is the simultaneous focusing of the 20 beams onto a microscopically small target. The problem is compounded by the requirements to minimize the amount of glass in the beam path and to work at various wavelengths - 1.05 μm, .52 μm and .35 μm.

We have minimized the glass in the system by making the lens also serve as a vacuum window. Accordingly, the focusing mechanism must work against the 5000 kg force of atmospheric pressure. The lens must be strong enough to withstand this pressure safely and the lens must be sealed to the chamber with a large bellows.

The focal length of the lens at .35 μm is about 312 mm shorter than at 1.05 μm, due to dispersion of fused silica. To provide a focusing range at each wavelength, the travel of the Z axis will be about 350 mm.

Lateral shift of the focal spot is 20 mm from center. All travels are powered by stepping motors and controlled from the central control room. Positions are determined by optical digital encoders to within .002 mm.

To diagnose the frequency converted beam, we have provided an uncoated surface which will reflect about 4% of the beam back through the turning mirrors to a diagnostics sensor. This surface is on the back of the second element of the two-element lens. Element spacing is variable to account for color changes and the second element is tiltable to aim the return beam back to the output sensor.

The lens positioner design is shown in Fig. 4a. An artist's concept drawing, showing the scale of the lens positioner, is shown in Fig. 4b. As an integral part of the lens positioner we have included the harmonic generation package, beam dumps to absorb unwanted unconverted light, alignment cross hairs and screens to aid in centering the beam.

Target Support

To support targets in the chamber, we will use a remotely controlled positioner, with four degrees of freedom, that will put them within 5 μm of the desired location. Controls for the target positioner will be integrated into the Novalink control system. Provision will also be made for handling cryogenic targets (and maintaining them in the frozen state) throughout installation, alignment, and exposure.

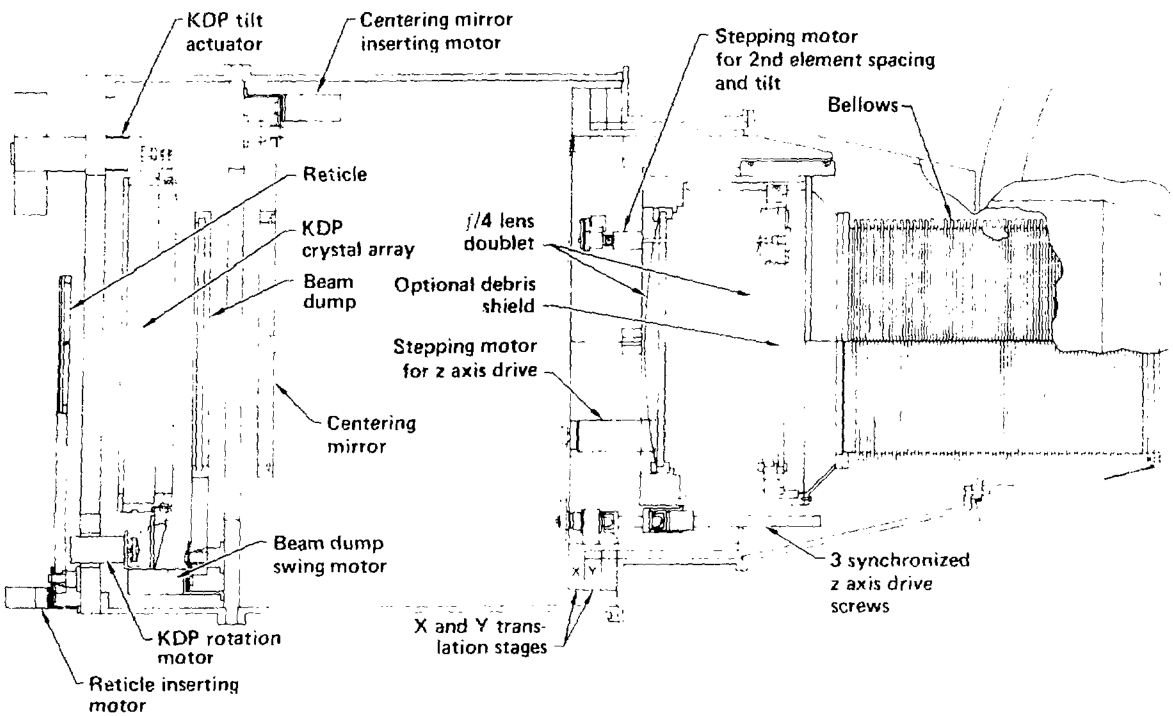

Fig. 4a - Nova lens positioner, using a two element f/4.0 lens. The first element is the vacuum barrier.

Target Alignment

We have a four step plan for aligning the laser beams to the target:

- First, a surrogate target is placed in the geometric center of the chamber. Since all target diagnostic sensors are aligned precisely to that point, the location must not vary from shot to shot.
- Second, all beams are focused to this center position by means of lens positioners, which are guided by images reflected from a spherical surrogate target into the output sensors or by images recorded directly on a CCD array used as a surrogate target.
- Third, the focal points are repositioned to various locations defined by the specific target to be irradiated. Each lens can be individually positioned to any spot within a 2 cm diam sphere.
- Fourth, the surrogate is replaced by the actual target. Its position must be identical to that of the surrogate - within 5 μm of true center, as verified by a reliable optical instrument.

The center of the target chamber will be established by the intersection of three optical lines of sight, as defined by three optical telemicroscopes - called Target Alignment and Verification Instruments (TAVI). These instruments will be installed on very rigid mounts and aligned to a common center. They must then retain that alignment under long-term conditions of vacuum or atmospheric pressure, thermal shock from high-yield targets, and accidental impacts during normal operations.

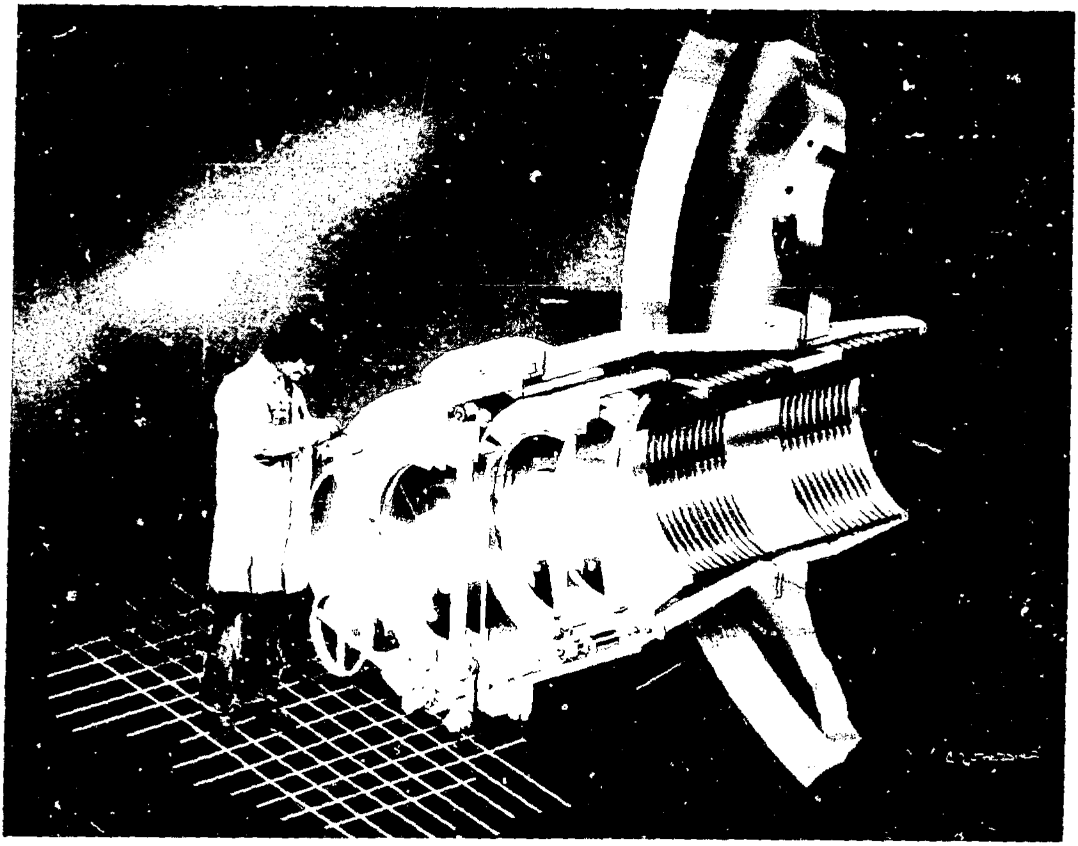

Fig. 4b - Artist's concept of the Nova lens positioner.

The TAVIs will have a field of view that will adequately cover all foreseeable targets and surrogates, as well as adequate resolution for positioning them to within 5 μm of the true center. We will use a CCD camera with an active area of 7.5 by 9.8 mm and a resolution of about 60 μm, so we will need variable magnification for viewing targets. Magnifications of 1/4, 1, 4 and 10 will be available through a turret-mounted lens system.

Our concept for meeting Nova requirements has evolved by extending Shiva designs in light of our operating experience. The schematic diagram in Fig. 5 shows a cross-sectional view of the main subunits in a single TAVI - an optical transfer, an image-viewing stage, and a control assembly.

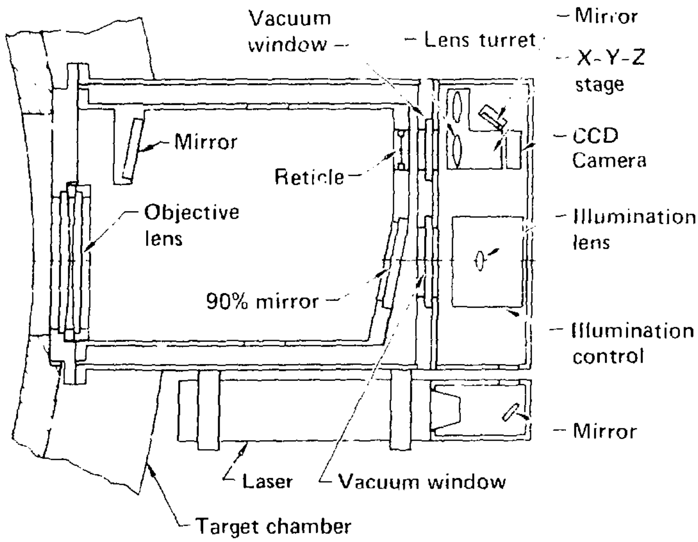

Fig. 5 - Arrangement of the Nova Target Alignment and Verification Instrument (TAVI)

The optical transfer requires maximum stability, which is accomplished by building the relay structure as a single unit and by mounting it ruggedly, coupled closely to the target chamber. It is completely within the vacuum and is isolated from the housing, which also provides protection from unauthorized adjustment and accidental impact during operations. To add rigidity to the housing and to conserve space in the experimental area, the optical path is folded.

The optical transfer will form a full-size image of the target on a reticle, all within the vacuum. The image will be viewed through a vacuum window by the image-viewing stage.

In response to electrical commands, the image viewing stage will move in three axes - within a 25 mm diam by 25 mm long volume - to measure target image features at the various magnifications. The CCD camera will move with the turret, thereby maintaining alignment and focus at all positions in the image volume.

Target illumination will be provided by a small He-Ne laser, which will use beam splitters and the imaging optics to provide both front and back illumination. Beam intensity will be made continuously variable by means of rotating polarization plates. For back illumination, the beam will pass the target and be reflected by an annular mirror on the far side of the target chamber. The return beam, being directed precisely toward the TAVI objective, will be efficiently collected. The diameter and location of the front illumination beam will be controlled to illuminate only that portion of the target being imaged at the time.

Target Diagnostics

We have provided ports in the central ring and the hemispherical heads for an array of target diagnostics instruments. Instruments sensitive to neutron or gamma pulses will be located in the diagnostics loft, behind the concrete shielding wall, and will be connected to the target chamber by vacuum line-of-sight pipes. They include instruments with synthetic plastic fluors and photomultiplier tubes or fast electronic circuits (such as the filter-fluorescer detector and the high-speed streak cameras). Intrinsically hard instruments, such as the calorimeters and Dante fast x-ray detectors, can be mounted on shorter pipes, within the target room.

All ports will be precisely located in spherical coordinates. In most cases, they will have a standard 8 in. dia. to allow diagnostics to be interchanged between locations or even between different facilities, such as to Novette. Each instrument package will have a valve in the line-of-sight pipe to isolate it from the target chamber. Control of these valves will be integrated into the Novalink system. This will allow any components to be evacuated separately and help avoid vacuum accidents.

Target Diagnostics Data Acquisition and Control

Nova target diagnostics will provide target data-acquisition and control functions, as outlined in a paper by J. Severyn in this session. CAMAC and LSI-11 interfaces will be used on most computer controlled data acquisition units. Our basic philosophy is to use standard acquisition and digitizing hardware from Shiva and Argus and to add hardware and software to integrate the target diagnostics into Nova's central controls. We will be supporting IEEE-488 Buss interfaces on Nova since many newer instruments use this standard computer interface.

The Nova target-diagnostics system will be operated primarily from the control-room consoles, using Ramtek touch-activated, color-graphics screens. The system will be experiment-oriented and menu-driven. The operator will first select an experiment type and then the diagnostics to be included in the experiment. Additions or deletions can then be made in the mix of acquisition modules for each diagnostic. An operator will be able to build an acquisition configuration from scratch or to use a file that describes a previous shot configuration.

Remote-control panels will also be placed in the diagnostics loft and in the switchyard near the target diagnostics, allowing operational checkouts to be performed locally. These remote panels will be interfaced to the control room, allowing the control room computers to maintain the updated status of the entire system. Nova target diagnostics will rely heavily on the hardware and software tools developed by Nova central controls.

10. LASER SEQUENCING, SYNCHRONIZATION, AND SAFETY SYSTEMS

This chapter presents an overview of the sequencing of Nova operations leading up to propagation of the optical pulse. Control techniques include checklists, computer controlled sequencing, programmable logic timers and oscillator electronics. Ensuring personnel safety during laser operation is a safety interlock system which is designed to be both independent and compatible with the laser control system.

The steps required to operate the Nova laser occur in a predefined sequence and span a time of many minutes. Early activities relate to alignment of the laser chains and setup of laser/target diagnostic sub-systems. These steps are semi-automatic whereby computer programs assist operators in completing a checklist of setup operations. When all preliminary setup is accomplished, an automatic sequencer program then controls and monitors systems for the final minute. During this time period, the energy storage capacitor banks are charged. At ten milliseconds prior to switchout of the optical pulse, control of the laser systems is transferred from the computer to integrated logic timers. One of the timers activates the master oscillator fast timing system at switchout minus one microsecond. The oscillator electronics then generates a sequence of triggers accurate to one nanosecond.

Of primary importance during the operation of the laser is the safety of all personnel. Potential hazards include high voltage, high intensity laser beams and radiation from high energy target shots. The system of barriers, sensors, displays and controls specifically designed to prevent personnel hazards is called the Safety Interlock System.

Nova is a powerful neodymium-doped glass laser facility intended to produce and characterize ICF micorexplosions. Controlling this laser is a sophisticated computer network interfaced with a variety of electrical, electro-mechnical and electro-optical devices; used to mechanize and automate alignment of optical components, perform diagnostic testing of laser/target performance and to provide real-time control of laser operations. This last function is performed by the Power Conditioning Control System. It 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.

The control system architecture (Figure 1) is based on the use of multiple computers exchanging information via a shared memory and communicating with laser devices via 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 is connected with each device that requires synchronization or control during a shot sequence. Synchronization via

NOVABUS is accurate to 1 μs; synchronization of devices requiring sub-microsecond 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 less than 1 ns in critical applications.

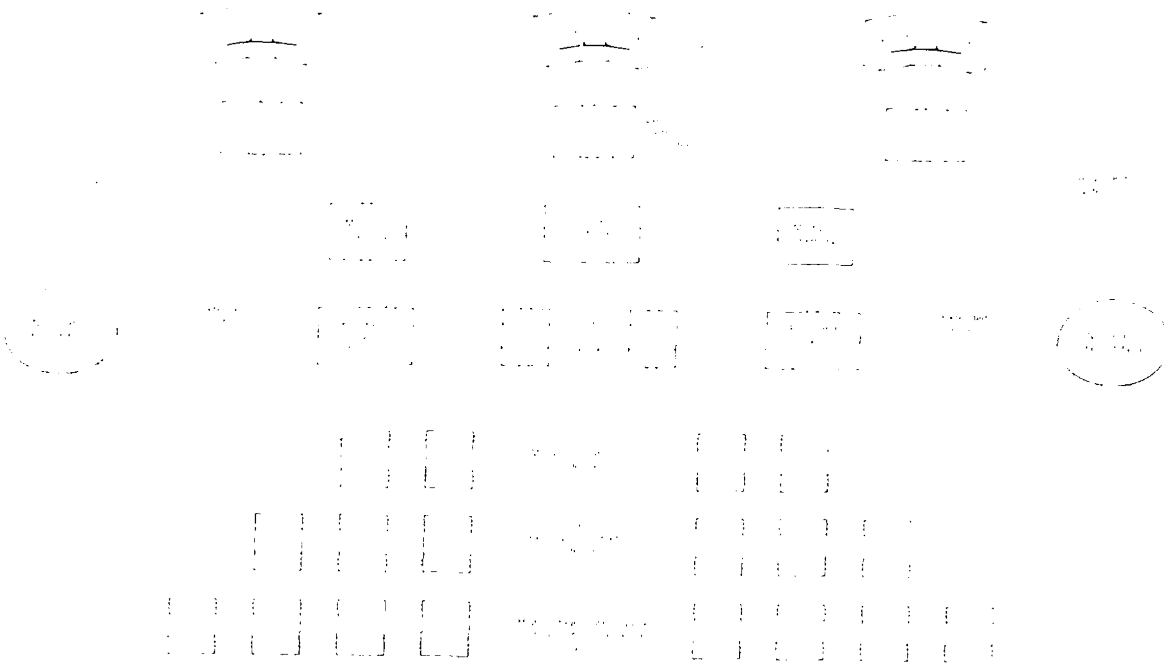

Fig. 1 - Block Diagram of the Nova Power Conditioning Control System

Laser Sequencing and Synchronization

All mechanical, optical and electrical components of the Nova system must function in a coordinated manner. Failure of any component to perform its' design function results in degraded laser performance. Therefore, validation of all laser subsystems is accomplished prior to propogation of the laser pulse. Furthermore, failure of certain key components can damage the laser itself. For example, an early breakdown of the railgap portion of the plasma shutter could cause reflection of the full energy laser pulse back through the laser chain with consequent damage to several costly 46 cm aperture optical components.

Preparation of the laser involves system, subsystem and component verification by operators in a pre-defined set of diagnostic tests. One such test, key to prevention of flashlamp failure at full power, involves testing of all three thousand circuits at reduced energy for waveform anomalies. These tests ensure that each system component is working properly and that interfaces with other components are properly configured. The sequence of testing is ordered to provide for the dependency of one system on another. Combined subsystem or integrated testing validates the interfaces between sub-systems. The end result is confirmation that all systems are functional and ready to support operation of the laser.

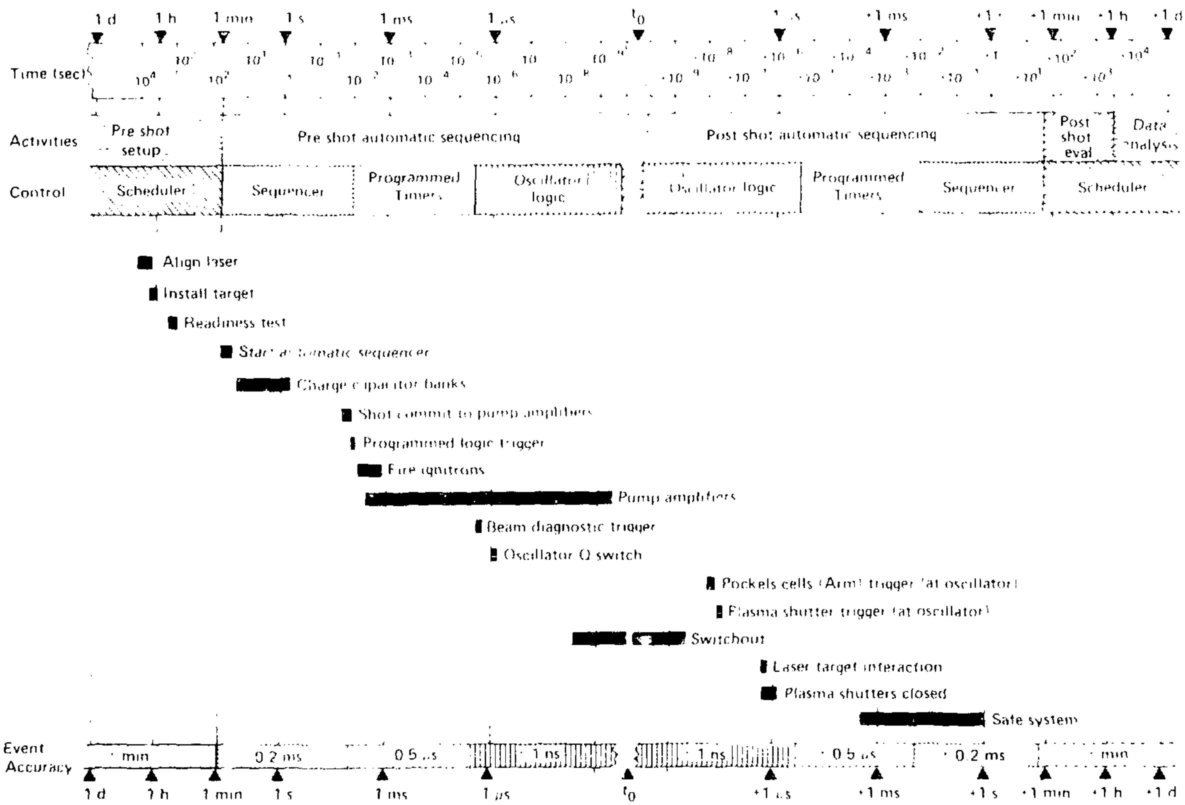

Fig. 2 - Event Timeline for Nova Operations Drawn on a Logarithmic Time Scale

Tasks associated with preparing the laser/target systems include manual setups, semi-automatic activities where computers assist operators and fully automatic tests under computer control. Figure 2 illustrates the major tasks associated with laser operation (note the logarithmic time scale). Early scheduled events are associated with time measured in minutes and seconds while events occurring during the propogation of the laser pulse are measured in nanoseconds and picoseconds. Event timing requirements for controlling elements of the laser system span 12 orders of magnitude. This presents a control problem that is unique to laser fusion. The design of a control system to conform to this wide range of requirements is based on the use of computers and programmed logic systems. Operationally, the control system is organized into three categories where each category is assoicated with a different control technique and covers a different time span. These categories are tabulated in Figure 3 and described in the following paragraphs.

Time period*	Major tasks	Timing required	System control
— to −10 hrs	Maintenance	± minutes	Computer assisted manual operations
−10 hrs to −1 min	Laser alignment Target installation	± minutes	Scheduler checklist
−1 min to −10 ms	Charge banks	± 0.2 ms	Interrupt driven computer operations
−10 ms to −1 μs	Fire ignitrons System triggers	± 0.5 μs	Computer initialized programmed logic
−1 μs to +1 μs	Laser switchout System triggers	± 1 ns	Master oscillator electronics
+1 μs to +30 sec	Safe system	± 0.2 ms	Interrupt driven computer operations
+30 sec to +1 hr	Quick look Evaluation	± minutes	Scheduler checklist
+1 hr to —	Data analysis	± hours	Computer assisted manual operations

*Relative to shot time

Fig. 3 - Table of Events Associated with a Laser/Target Operation

Scheduler (-hours to -1 minute)

Figure 4 illustrates the major activities in preparing for a laser operation. This data reflects the Shiva laser operation and does not apply directly to the Nova laser. The difference will be a shortened time-span for Nova preparation because of increased automation of setup tasks. Each block of Figure 4 represents a set of tasks that are managed via the use of a checklist. At each step, the Shot Director verfies that the step was successfully completed before moving on to the next step. Checklists of this nature are readily automated simply by having a computer prompt the Shot Director of each decision point of the testing sequence. The computer can also perform much of the test data evaluation

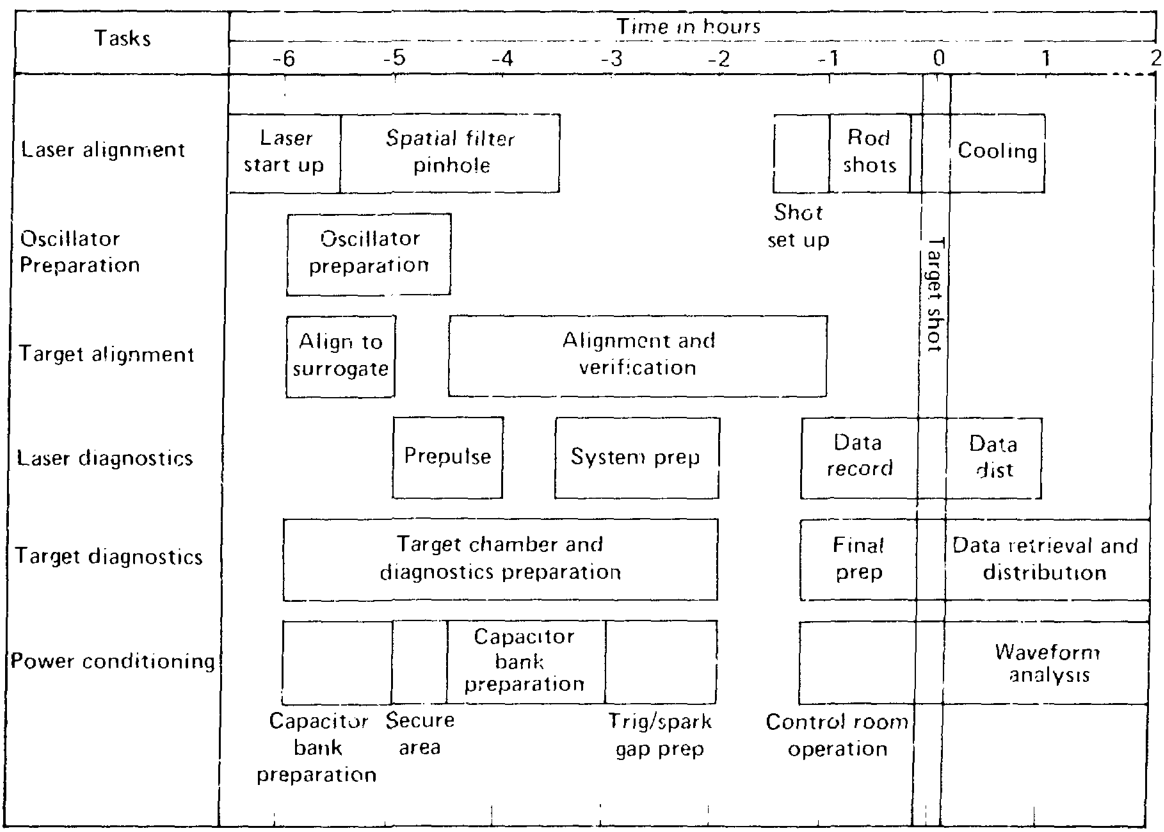

Fig. 4 - Task Timeline for the Shiva Laser

freeing the Shot Director from routine tasks. Anomalies are rapidly brought to the attention of the Shot Director so that he can either modify the test, repeat the test or initiate diagnostic procedures. An automated checklist program of this nature is typically referred to as a scheduler. The scheduler assists the Shot Director with validation of the system while simultaneously recording data related to all tests conducted.

The scheduler oversees the preparation of the laser and target systems; when all sub-systems are determined to be ready for a shot, the scheduler initiates an automatic sequencer which executes a predefined set of commands and diagnostic routines to complete the final system preparation. The primary difference between the Scheduler and the Sequencer is that the scheduler is event driven while the sequences is time driven. The scheduler progresses from event to event where the time span to complete a given event is not fixed. The sequencer on the other hand is time ordered with each event occurring at a specific time relative to propogation of the optical pulse. The sequencer monitors the entire system for proper operation and will automatically 'hold' in the event of a system anomaly. Such anomalies include ignitron prefires, plasma shutter prefires, interlock breakage or failure of a device to respond to commands. The Shot Director can 'hold' or 'abort' the scheduler or sequencer at any time he desires.

<u>Auto-sequencer (-1 minute to -10 ms)</u>

At one minute prior to switchout of the laser pulse, the timing of events becomes more critical. These events are controlled by the automatic sequencer which consists of computer routes to perform control and diagnostic functions. Each sequencer event activates a routine at a predefined time measured in seconds and milliseconds preceeding laser pulse generation. Early sequencer channels are related to setup of the power conditioning system. At t-30 seconds, the sequencer initiates charging of the energy storage capacitor banks. By t-1 second, some 100 megajoules of electrical energy is stored and ready to be switched into the laser amplifiers. A key decision point occurs at switchout of the laser pulse minus 10 milliseconds. If, at this time, all systems are determined to be ready, the sequencer sends a Universal Trigger over the control system NOVABUS network. This global signal activates programmable timers throughout the laser facility. The commitment at this time is to pump the laser amplifiers but not necessarily to switchout a laser pulse. If pumping of the laser amplifiers occurs, the 100 megajoules of electrical energy is switched from the charged capacitor banks to the laser amplifier flashlamps. Removal of the resultant heat and stablization of the amplifer glass requires in excess of one hour. Thus, if the shot is aborted after t-10 msec, for any reason, an extensive delay is required before the next shot.

Programmable Timers (-10 ms to -1 s)

During the final milliseconds, the environment that the control system must function in changes drastically. Electromagnetic noise levels increase dramatically while timing requirements are tightened to microseconds. The pumping operation requires that the electrical energy stored in capacitors be transferred to the laser amplifiers in about 1 millisecond with a peak power in excess of 100,000 megawatts. Careful design of the pulsed power system ensures that only a small fraction of this power is radiated as noise. Even so, the noise is extreme when compared with required environmental conditions for TTL/ CMOS circuitry. Control system logic adjacent to the ignitron switches must not only survive but continue to operate throughout this noisy period. The most noise susceptible components are the fiber optic receivers of the NOVABUS control network. Since control signals to/from the control computer pass through these devices, control signals are subject to corruption during the high noise period. This problem is eliminated by storing commands in each device interface to be executed during the high noise interval. Device interfaces are loaded with timing information well before the pumping operation. Each device then operates independent of the control system for last 10 milliseconds prior to switchout. The timing information is loaded into device interface logic called programmable timers. All timers are activated simultaneously when the control computer sends the global Universal Trigger signal over the NOVABUS network. Programmable timers provide synchronized triggers to the devices listed in Figure 5 which includes the master oscillator.

Function	No. Timers	Fanout	End Usage
Osc synchronization	8	No	8
TV synchronization	1	Yes	6
Laser diag. sync.	6	Yes	92
Target diag. sync.	1	Yes	6
Ignitron triggers	226	No	226
	242		338

*Resolution = 1 microsecond
Jitter = ±200 nanosecond

Fig. 5 - Tabulation of Programmable Timer Channels for the Nova Laser

While the timers are running, the computer continues to monitor for abnormal conditions. If an 'abort' conditions arises, the computer sends a command directly to the oscillator to prevent switchout of the laser pulse. At t-1 μs, a timer signal initiates Q-switching of the oscillator; the oscillator then issues a sequence of triggers to laser devices requiring submicrosecond timing.

Oscillator Timing (-1 μs to +1 μs)

Electronics associated with the master oscillator is designed to produce timing signals with nanosecond resolution. Figure 6 is a block diagram of the oscillator timing system. The exact timing of each channel is loaded by the control computer into random access memory within the 'FAST TIMING CONTROL' block of Figure 6. Eight bit Shottky TTL counters clocked by the master r.f. oscillator output (divided by two) provide the

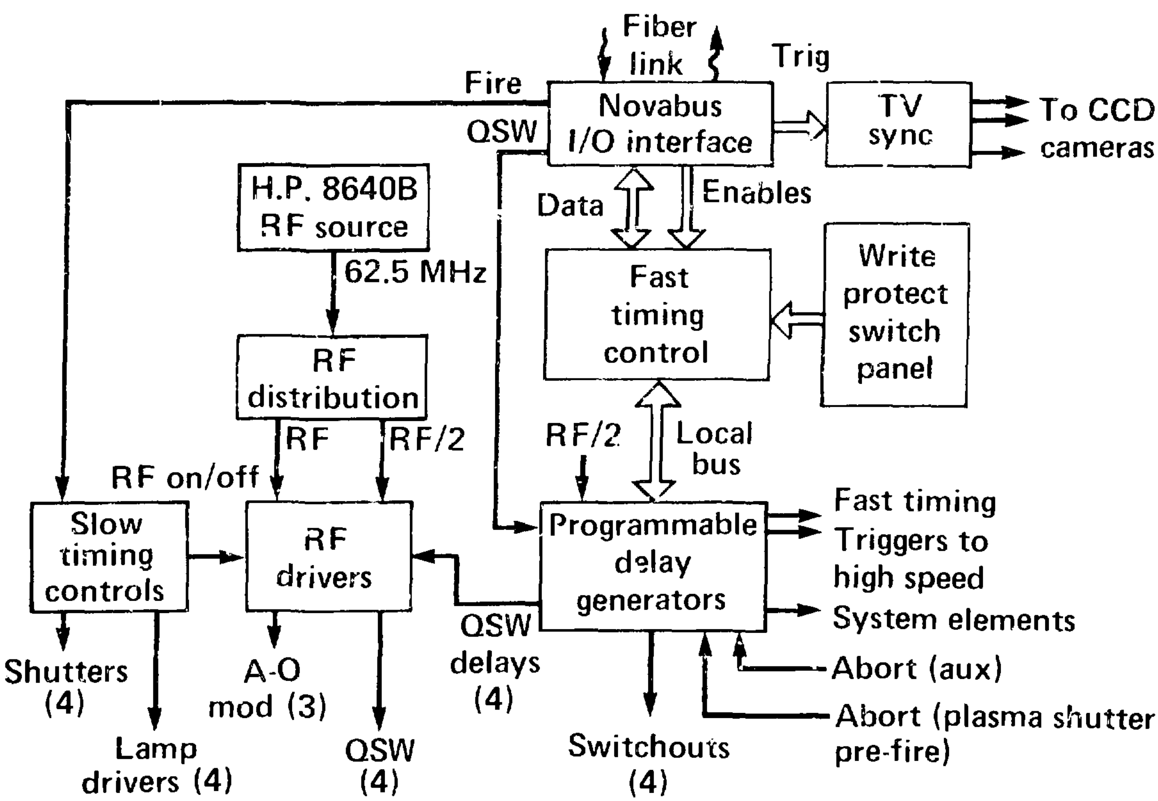

Fig. 6 - Block Diagram of the Oscillator Electronics Timing System

coarse timing. By choosing either the leading or trailing edge of the symmetrical 31.25 MHz clock, 16 nanosecond resolution is attained. Finally, programmable delay lines provide one nanosecond resolution. The capability to abort the switchout signal is also incorporated in the event of a plasma shutter prefire. This abort signal is by direct connection between the oscillator and plasma shutters.

Figure 7 illustrates the relationship of the timing pulses with respect to the propogation of the laser pulse. Note that certain control signals are launched after switchout of the laser pulse. Because of physical length differences, the gating signal reaches and activates its device prior to arrival of the laser pulse. Figure 8 itemizes the devices that receive fast timing triggers from the oscillator electronics.

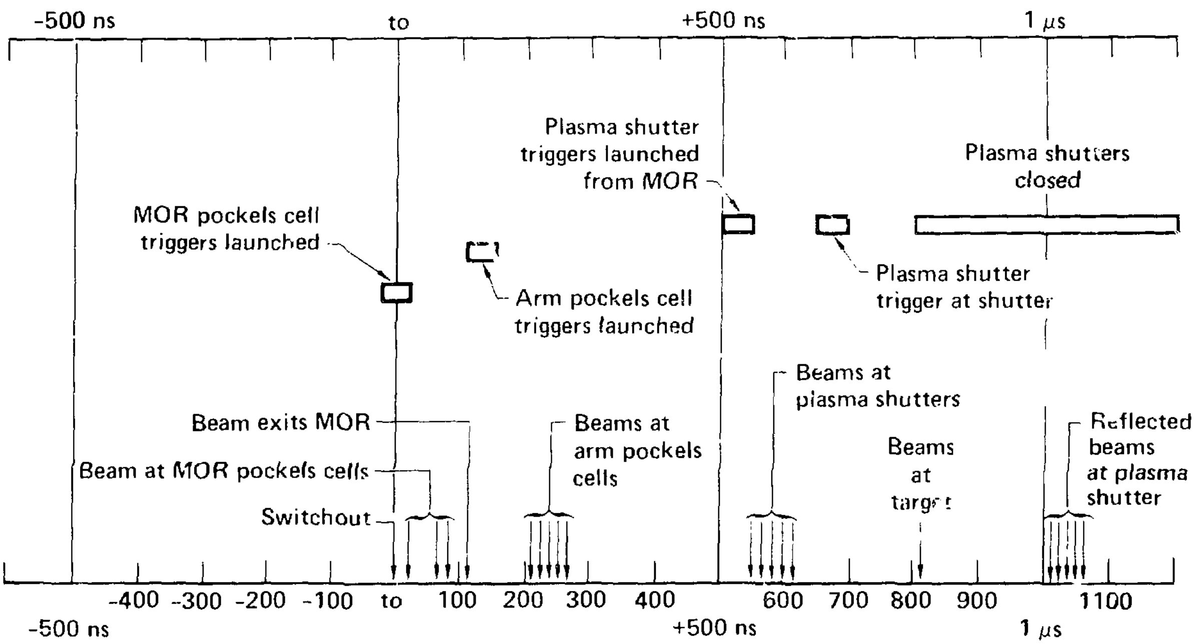

Fig. 7 - Event Timeline for Events Very Near to Laser/Target Interaction

Post Shot (+1 μs to + hours)

Tasks associated with diagnosing how the laser/ target performed begin immediately following the shot. Beam diagnostic data, target diagnostic data and power conditioning data recorded by numerous diagnostic devices are transferred to large computers for processing. This data base is used to determine how the overall system performed and to identify required adjustments prior to the next shot.

Function	No. Channels	Fanout	End Usage
Osc. Q-switch	4	No	4
Osc. switchout	4	No	4
Pockels cells	8	Yes	28
Plasma shutter	4	Yes	20
Beam diagnostics	20	Yes	126
Target diagnostics	2	Yes	6
	42		188

*Resolution = 1 nanoseconds
Jitter = ±100 picoseconds

Fig. 8 - Tabulation of Master Oscillator Timing Channels

Safety Systems

Associated with the operation of a high powered laser are potential hazards to personnel. High voltages, laser beams and radiation from targets must be contained and isolated from workers. Physical barriers, electrical interlocks, visual warning displays and audible warning messages are used to protect users. Identification of potential hazards is the responsibility of each system/project engineer. This identification occurs early in the design process and is periodically reviewed as the design matures. Potential hazards are presented in the relavent Design Review and documented on a Preliminary Hazards Analysis Form including recomendations to ameliorate the hazards.

Facility or system-wide safety criteria are implemented by a centralized interlock system. This system monitors doors, oscillator shutters, beam blocks, Run/Safe monitors and Panic boxes. It generates permissives to power supplies, entry doors and oscillator shutters. Interlocks may function either mechanically or electrically to deactivate, shield or de-energize the hazard involved whenever a nonauthorized entry is attempted. Electrical interlocks are implemented using redundant logic to ensure that a single point failure of the interlock logic will not produce a hazardous condition nor fail to detect a hazard. Operation of the interlock system is monitored by the computer system to detect any single failures. A single failure will not affect the laser operation but must be scheduled for repair by maintenance personnel. In addition to safety interlocks, the control room and MOR are electrically isolated from laser bay devices, target room devices and energy storage devices. This isolation is accomplished by using fiber optics to transmit and receive all control and diagnostic signals.

Interface between the human and the safety system takes many forms including physical barriers, visual displays, safety switches and audible warnings. The safety system is designed to provide the operator with visibility of potential hazards and give him methods to eliminate such hazards. Barriers are used to prevent entry of a person or a part of his body into a danger area. The type of barrier is determined by the nature of the hazard. Signs are posted to inform persons of the hazards involved and any special precautions to be observed. Doors, gates, removable panels are locked and/or interlocked. Noninterlock barriers include beam-tubes, equipment cabinets, shields and barricades. The safety system provides for automatic safing in the event of personnel entry into a hazardous area.

11. THE NOVA CONTROL SYSTEM - GOALS, ARCHITECTURE, AND CENTRAL SYSTEM DESIGN

Control and data acquisition functions for the Nova Laser and Target Irradiation facility 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 fundamental subsystems (Power Conditioning, Alignment, Laser Diagnostics and Target Diagnostics) to optimize internal design and organization according to their specific 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:

Power Conditioning - Capacitor bank activation, laser firing, and system timing.
Alignment - Laser and target alignment.
Laser Diagnostics - Measurement of beam energy and quality.
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 5,000 individual control and data acquisition elements are supported. These include:

- Stepping Motors
- Calorimeters
- Interlocks
- Transient Digitizers
- Video Images
- High Voltage Power Supplies
- 20 kV Digitizers
- 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 beam profiles. Specific requirements for subsystems are described in companion papers in this session. This paper will concentrate on the overall system architecture and the features of the Central Controls subsystem.

Design Objectives

The principal objective of the Nova control system is the control and diagnosis of the Nova laser and target systems. There is a second objective to design a system in which the cost of development and long-term facility operations can be reduced. To meet this objective, the following approaches have been implemented:

- *Centralized Control* - *Nova's fully integrated control system allows* geographically distributed operations to be performed by a limited number of personnel in a centralized control area.

- Commonality - A set of common hardware and software "tools" are employed in all subsystems, thus minimizing redundant development efforts to meet similar functionality requirements.

- Effective Use of Personnel - The developers of the common tools migrated into lead roles for the development of the subsystems which must use those tools. This reduced the need for a separate team of developers, and simplified the task of technology transfer into the subsystem efforts.

Design Criteria

The design criteria established for the Nova Control System are representative of those found in large distributed systems of this type. Major criteria motivating the system arechitecture are:

Reliability. This is achieved through several techniques:

Distributed Controls. Failure in one control unit does not affect the others.

Fault Tolerant Hardware. Self checking hardware is used, particularly in the area of fiber optic communications.

Fault Isolation. Optical isolation techniques prevent high voltage fault propagation.

Redundancy. Critical control system elements are redundantly designed.

Flexibility. The need to be adaptable to diverse and changing requirements is satisfied by:

Computer Based Architecture. Extendable hardware and software can meet evolving requirements.

Configuration Management Techniques. System changes are coordinated using a relational data base.

Performance. Simply stated, control system performance should not constrain the shot rate of the laser.

Image Processing. Automatic closed loop alignment using video based CCD camera sensors established a criteria for high speed image processing capability.

Communications. High volume data and time critical control functions dictate the use of a high speed data communications system capable of efficiently handling single "byte" as well as extended block transfers.

Integration. All subsystem control functions are to be integrated into a single, centrally operable control system. However, designers must retain flexibility to optimize the individual subsystem architectures.

Cost. Cost is primarily limited by budget. However, the price of development and operations with this integrated control system should fundamentally be less than that for a non-integrated system without a central support capability.

Functional Organization

Figure 1 illustrates the organization of this hierachically structured system divided into the four major functional areas. Digital Equipment Corporation LSI-11/23 microcomputers are used at the local control and data acquisition level to provide sufficient capability to align, fire, and acquire data from an experiment. Data for each of the

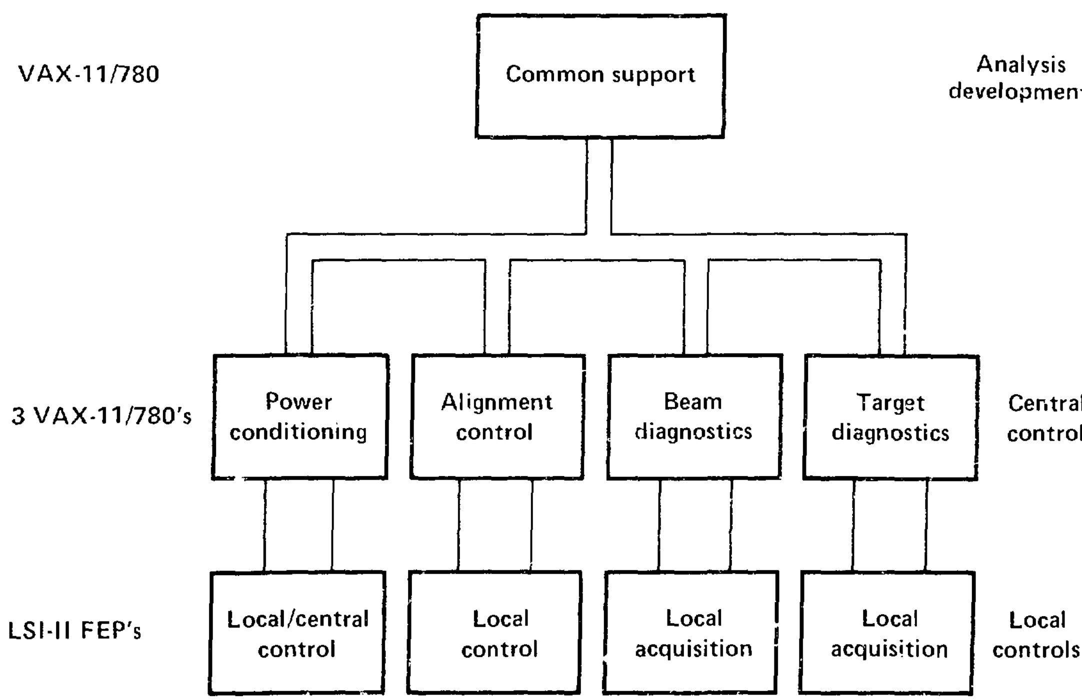

Fig. 1 - Multi-level Control System Functional Architecture

subsystems is collected, analyzed and integrated at the central control level with redundant VAX-11/780 computers. These also support a central operator capability in the Nova control room. Common resources such as large file storage, plotting output devices, and analysis packages reside at the uppermost level supported by a single large VAX-11/780 system.

Hardware Architecture

Distributed Local Control Computers. The hardware architecture of the Nova Control System is illustrated in Figure 2. The fundamental "building block" for local control and data acquisition functions is the LSI-11/23 microcomputer from Digital Equipment Corporation. The LSI-11's are packaged in an LLNL designed chassis (see Fig. 3) which provides power and I/O 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.

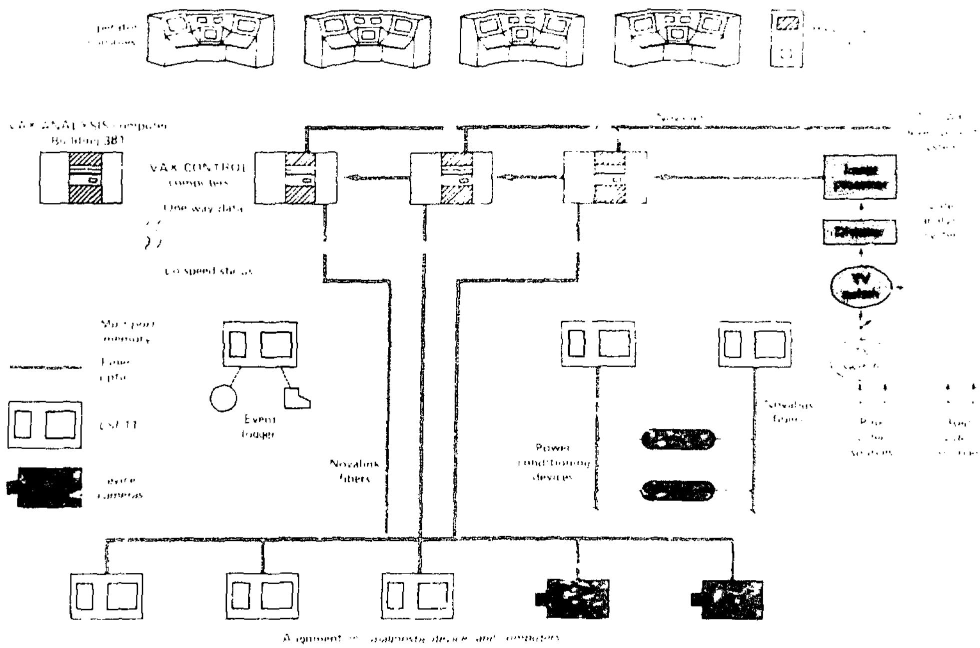

Fig. 2 - Nova Control System Architecture

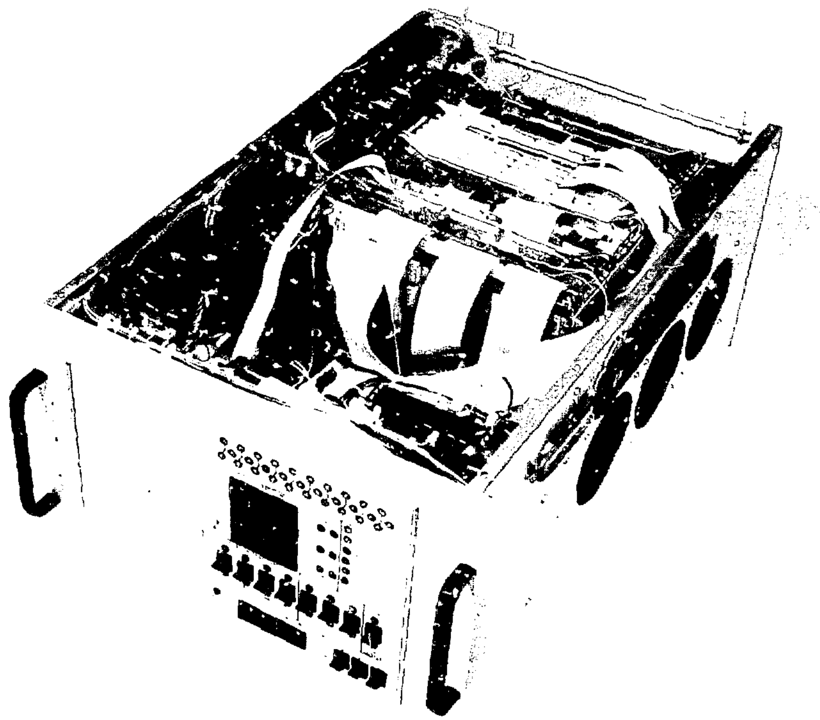

Fig. 3 - LSI-11/23 Stepping Motor Controller

Central Control Computers. The technically diverse control functions of the four fundamental subsystems are centralized and integrated in three Digital Equipment Corporation VAX-11/780 computers. These computers, interconnected with shared memory, share the load of central system operation and provide redundancy. Functions performed at this level include cross subsystem interlocks (synchronization), centralized operator control, configuration management, and data storage.

Data Communications. Two fiber optic communications systems, Novanet and the Power Conditioning subsystem's Novabus, provide high speed data transfers to remote locations through the facility. Novabus has been designed to maximize control system data transfer speed to remote devices. The Novalink system supports computer-to-computer as well as computer-to-device transfers for the Alignment and Diagnostics subsystems. Devices serviced by Novabus are connected to the central computers via multi-port memories attached to controller LSI-11's. All elements connected via Novalink, including the three central computers, form nodes in a network in which any Node can "talk" to any other node.

Novalink and Novabus are discussed in Chapters 10 and 12.

Central Operator Consoles. Four fully programmable central operator consoles provide a flexible high performance operations interface into the Nova control system. Each console (see Fig. 4) is designed for a single operator who can view status and initiate control functions for any of the four fundamental control subsystems. The console consists of three mid-resolution (512 x 640) 19" color displays, two of which provide status information. The centrally mounted third screen, which typically displays an operator selection menu, is overlayed with a transparent touch panel to translate operator selections into screen coordinates. The touch panel is augmented by a force operated joystick (for stepping motor control) and a numeric keyboard.

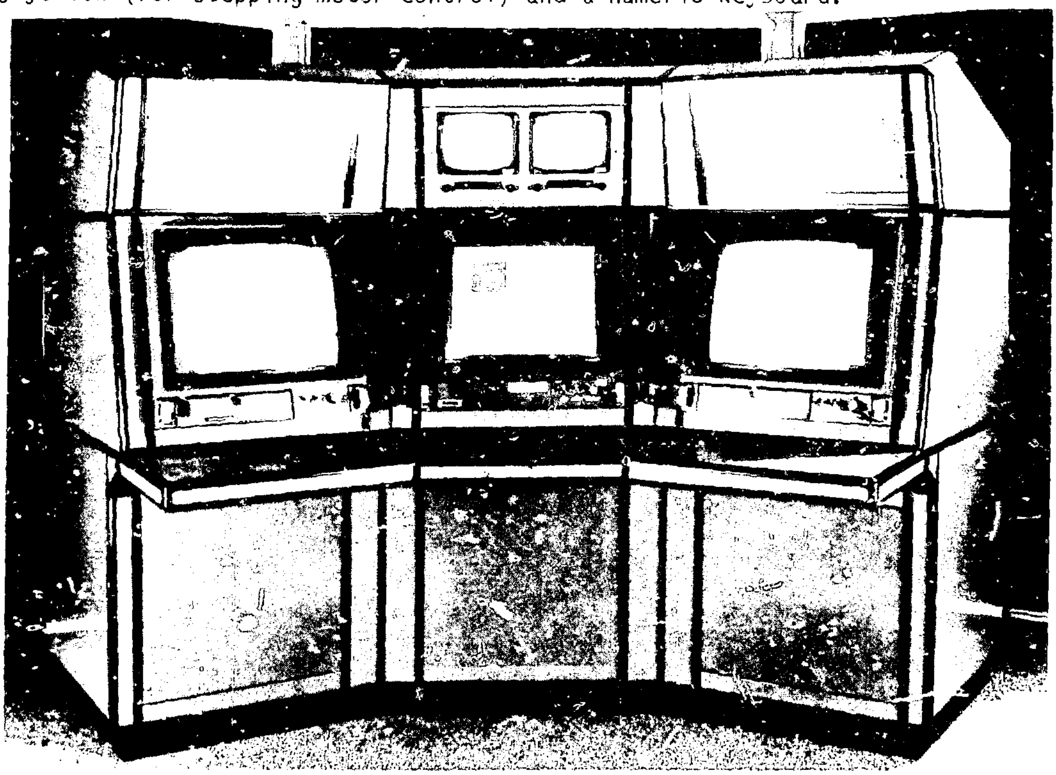

Fig. 4 - Nova Operator Console

Event Logger. An event logging facility built upon a PDP-11/34 mini-computer connected via Novalink and multi-port memories to the control system, provides an independent station at which significant time stamped control system events are displayed and stored. This capability results in an integrated event log which is used to track operations activity and to analyze the cause and effect of control or laser system malfunctions.

Image Processing. The control system must be capable of rapid analysis of video beam images which are generated by the CCD alignment system cameras. To accomplish this, the VAX-11/780, with its virtual memory capability providing the address space required for complex image analysis, is augmented by a high speed auxiliary image processing system. It consists of a Quantex video frame digitizer with 256 x 256 addressability interfaced directly to a Floating Point System FPS-120B array processor. The array processor is interfaced to a central VAX-11/780 computer through its I/O bus (UNIBUS). This auxiliary system increases the speed of image processing by a factor of 100, allowing all closed loop image analyses to be performed by a single set of hardware at the targeted rate of one full analysis (e.g., pinhole image center point detection) every second. Selection of the video sensor source to be analyzed is accomplished through a computer controlled TV switching system.

Principal Software Elements

Software developed to meet commonly required needs in the Nova Control System was designed according to an additional criteria: Subsystem application programmers, familiar with the requirement and terminology of their own subsystems, should employ familiar control system as opposed to computer science concepts when using support software.

Console Display System. An example which meets this requirement is the operator console support software. As noted previously, the console is primarily a high performance graphics system with a two dimensional coordinate input capability. However, the software interface allows the programmer to display and select items by name (e.g. SPATIAL-FILTER-12) as opposed to by screen coordinates (see Fig. 5).

Data Communication through Shared Tables

During the early design stages of Nova, it was recognized that, for the subsystem engineers, the most clearly understood method of program to program communication was through shared tables of data. The ability to share tables between programs in the same computer, programs residing in computers connected by Novalink has been provided using a single set of interface routines called NSM (Network Shared Memory) (see Fig. 6). NSM, therefore, provides a simple control system oriented interface to the extensive network functions of Novanet, the software system which supports the Novalink hardware. Since the interface to the shared tables is independent of the physical data transfer medium, uniform methods of communicating between programs in the same and separate computers can be used. This decreases programming effort and increases system maintainability.

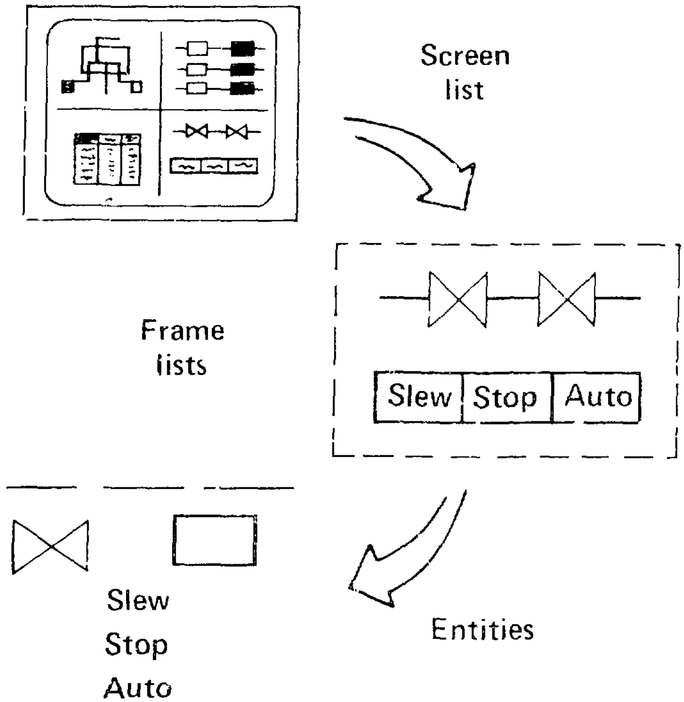

Fig. 5 - Graphics Software Deals with Laser Elements

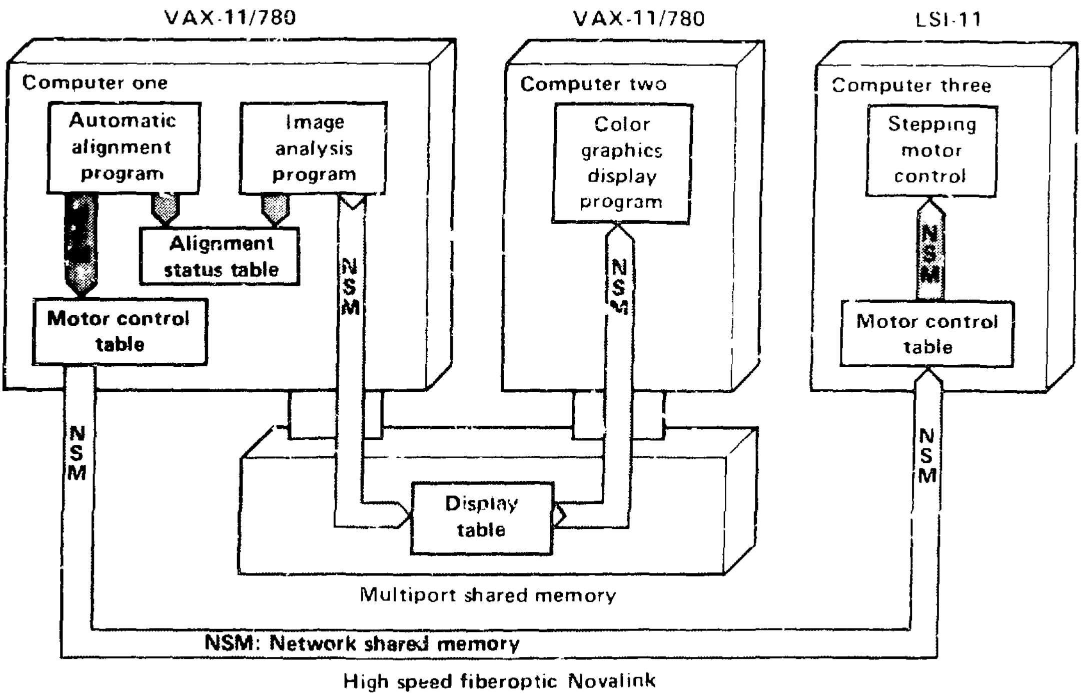

Fig. 6 - Programs in the Same or Different Computers Use Shared Tables to Transfer Data

Configuration and Data Management

The configuration management system for Nova (see Fig. 7) is designed to provide a single source for all configuration related information needed by the developers and the operating software.. In addition, data base management of raw as well as processed data is required to ensure the long-term accessibility and usefulness of collected shot information.

These tasks are accomplished using a combination of a special purpose ISAM data base (for unprocessed data) and relational data bases managed by ORACLE system (obtained from Relational Software, Inc.). The ISAM data base for unprocessed shot data contains software data structures which correspond to the data to ensure long-term accessibility of shot information.

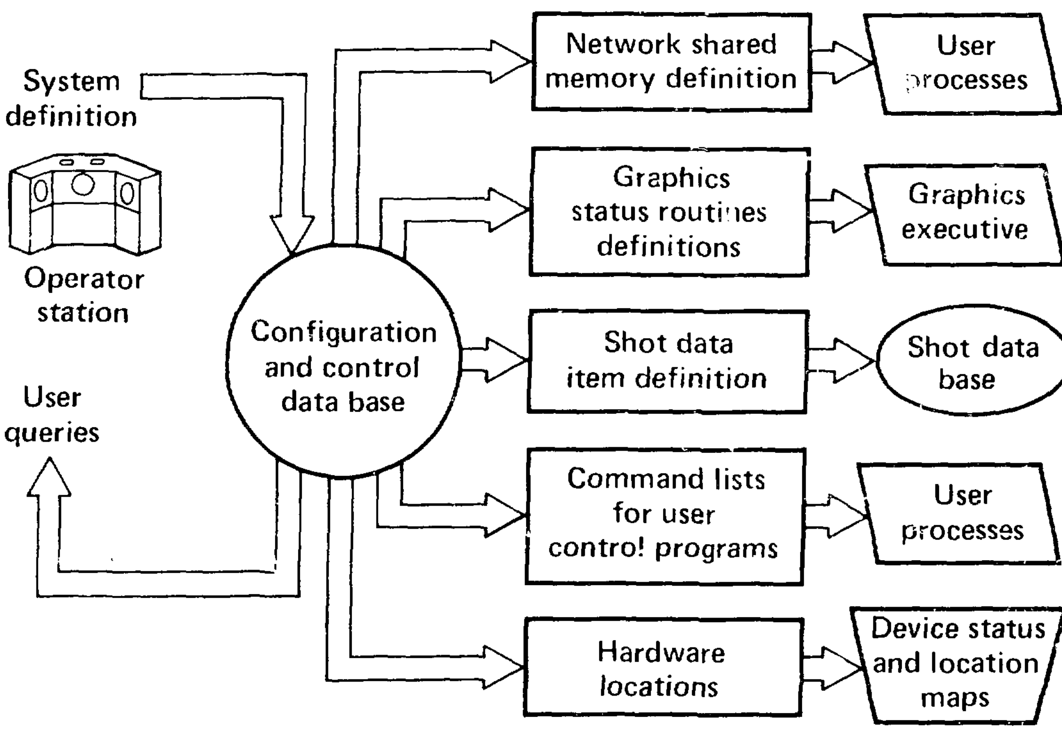

Fig. 7 - Nova Configuration Data Management

PRAXIS--A Control System Implementation Language

A major software development in Nova has been the design and implementation of the PRAXIS programming language (see Fig. 8). PRAXIS was conceived originally as "COL" by Bolt, Beranek & Newman, Inc., (BBN). It was a response to one of the early DOD programming language specifications 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 which 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.

```
Declare
    Vector is structure
    Routine : interrupt procedure () initially service
    Status  : logical initially 8#340
Endstructure

    Clock   : volatile location (8!100) vector
    Ticks   : static integer initially 0

Enddeclare

Interrupt procedure service ()
    Ticks *= + 1

Endprocedure ¼service½ ()
```

Fig. 8 - Interrupt Driven Clock Routine

PRAXIS is a high level block structured language supporting real time constructs, separate module compilation, and extensive data type checking. Written in its own source language, PRAXIS currently generates code for both VAX and LSI-11 computers.

A Typical Application

A typical application is the automatic alignment of the laser beam via mirror adjustment using cross hair reference points (see Fig. 9). The mirror is mounted on a stepping motor controlled translator stage. Activity begins when the operator selects the automatic alignment operation at the center screen of an operator console. This selection activates the closed loop alignment process software in a central VAX-11/780. The alignment process selects the sensor's video image for input to the frame digitizer where it is stored and subsequently analyzed by software in the attached array processor. The offset of the two reference cross hairs is determined and passed back to the VAX resident alignment process. If a correction is necessary, the number of steps to move the mirror translator motors is put into a data table. The NSM system sends this data table to the remote stepping motor controller LSI-11 (which sees an exact copy). This LSI-11 steps the motors moving the mirror. The alignment process generally repeats the image analysis at this point to ensure the integrity of alignment.

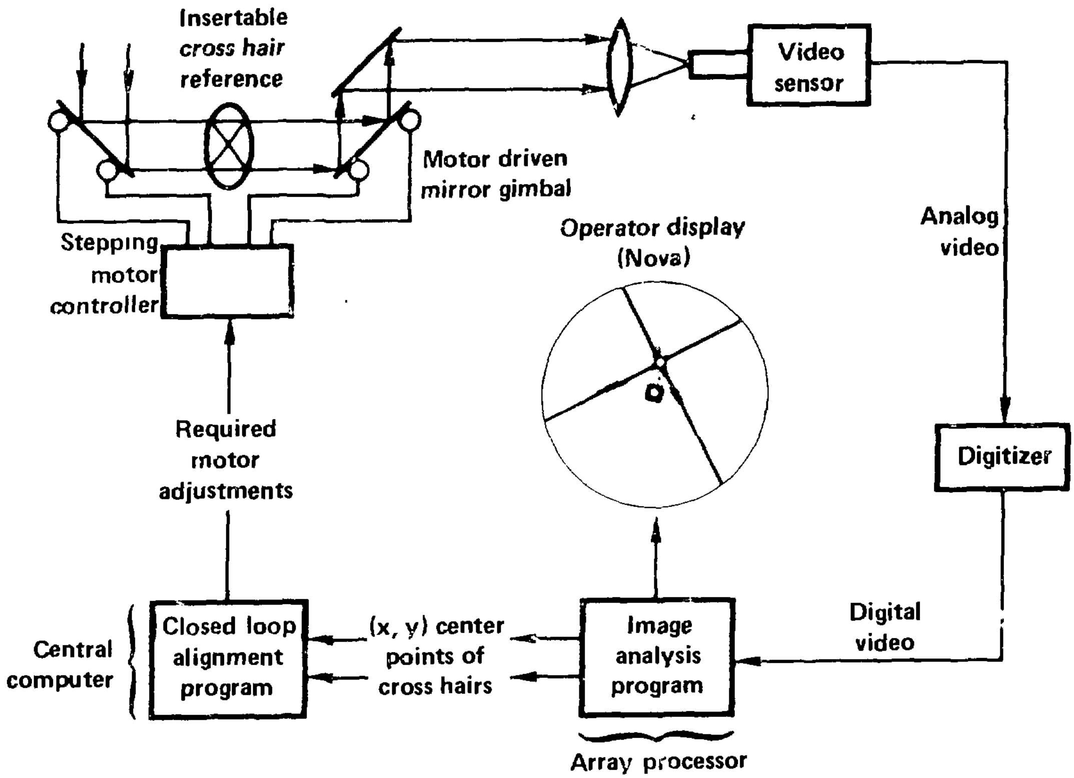

Fig. 9 - Closed Loop Alignment through Image Processing

Status and Concluding Remarks

The control system components and architecture described here were demonstrated in November, 1980, using automatic closed loop alignment as the text application. Initial installation of the first of these control systems is scheduled for December, 1981, on the Novette laser, a two beam precursor to Nova.

The control system architecture for Nova provides a unifying framework within which developers of the individual subsystems retain the flexibility to optimize designs to fit their application. A total of 16 hardware and software products in the areas of operator controls, data management, data communications, and special systems have been developed. These form a set of tools supporting common functions across subsystems while providing the foundation for the integrated and centralized control of the Nova laser system.

12. NOVANET, A LOCAL COMPUTER NETWORK, AND NOVA TARGET DATA ACQUISITION SYSTEM

This chapter will cover two topics. The first is Novanet, 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 3 VAX 11/780 computers, approximately 50 LSI-11 processors and 15 charge coupled device (CCD) TV cameras. All transfers over Novanet, including the transfer of digitized video information, utilize direct memory access (DMA) techniques. The second topic discusses the Nova Target Data Acquisition and Vacuum Control System which uses CAMAC instrumentation interfaces and LSI-11 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 picosecond resolution CCD streak cameras. Architecture, system design philosophy, control and data flow will be presented.

Novanet

The local computer control system for the Nova laser involves 50 computers, some processing digitized video information, which requires the rapid exchange of large amounts of digital data. Several standards for local communication systems have recently been adopted but very little working hardware is presently available. The situation is especially critical if the criteria includes networking of small, read-only-memory processors that would be commonly used in dedicated applications such as remote data acquisition or stepping motor control.

The Novanet local control network also solves some operational problems associated with the commonly proposed "bus" oriented networks by utilizing the advantages of both the "star" and the "bus" network topology (see Fig. 1). Novanet physical connections to the 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 feature that will be commonly used in the Nova control system 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 capbility of segmenting into 64 separate sub-networks. Once the large volume data is tranferred (for example, moved 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.

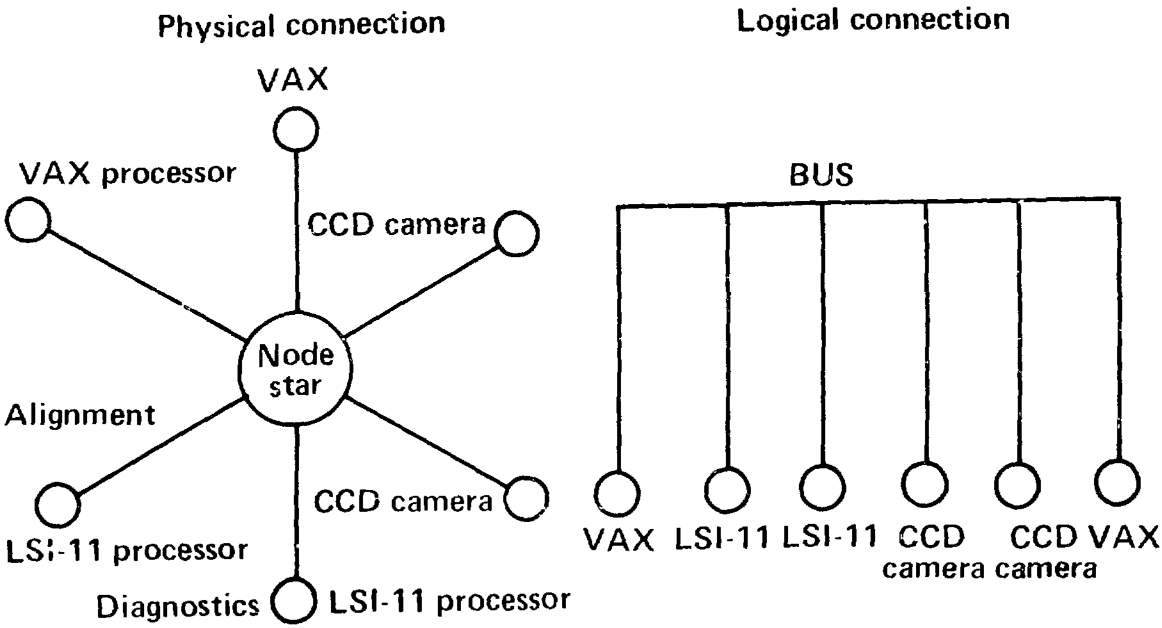

Fig. 1 - Novanet Physical vs. Logical Connection

Basic Protocol

Novanet utilizes a request-reply handshake scheme for all transactions including passing of the network "master" status. At any one instant, only one processor in the network is the "network master". The net master is the only node that is capable of initiating transfers at that instant. If other nodes wish to start a transfer, they must first request and be granted net master status. This has been referred to as "token passing" and does not depend on collision detection network contention schemes. The token passing of the net master status requires a maximum of 10 milliseconds for 256 nodes, but is accomplished automatically by the microprogrammed state machine on the network interfaces. Thus, the software at each node processor need not be concerned with the "bottom level" protocol.

Hardware

All connections to the Node Star are made using fiber optic cable with separate transmit and receive fibers utilizing a line rate of 10 megabits per second. All transfers are hardware error checked by on-board circuitry on each node interface. Transfers to and from the various nodes are accomplished using direct memory access (DMA) techniques, to minimize the communication load on the node computers. The lowest level of the communication line protocol is implemented directly in microcoded state machines on each network node interface. Thus, the lowest level (and most often used) handshake and data transfer protocol is done in hardware, further increasing system transfer speeds. We presently support Novanet with four different types of hardware.

Master/Slave Controller (MSC). The Master/Slave Controller consists of two printed circuit boards designed to DEC Q-Bus specifications. These board pairs are the interface to LSI-11 and VAX processors. Connection to a VAX or PDP-11 is accomplished using the UNIBUS and a Q-Bus to UNIBUS converter. The decision was made to use the Q-Bus as our standard interface as it is the normal LSI-11 processor bus. (LSI-11s outnumber VAX and PDP-11 processors by at least a factor of ten in our system). The two board set consists of a DMA control board and a line controller board. The DMA board provides the processor interface registers and the circuitry to directly deposit data into or read data from the processor's memory. The line controller contains the optical transceiver and the microprogrammed state machine that implements the line protocol.

Multiple Device Interface (MDI). This interface consists of three boards that are inserted in the memory controller of the LLNL designed Charge Coupled Device (CCD) TV camera. This camera has the capability of digitizing and locally storing one TV frame. Thus, the MDI provides a way of controlling the camera and tranferring the digitized video information directly into the VAX with its disk storage capability.

Q-Bus Device Interface (QBDI). This interface allows the attachment of any Q-Bus, program controlled device to the network. It is a single card that is mounted in a Q-Bus backplane that takes the place of the normal LSI-11 processor. This allows network transfer of data and control signals to programmed input/output devices in locations where the capabilities of a full processor are not required.

Node Star. As previously mentioned, the node star allows a star physical connection topology to be logically considered as a bus connected system. The node star itself consists of one or more micro-node star boards, each capable of supporting 16 nodes on the network. Thus, a 48 node system would require 3 micro-node star boards in a chassis. The node star also has several unique features that aid in network maintenance and fault isolation. Because of the physical connection scheme, a faulty node can be electronically disconnected from the network. This allows network fault isolation to take place very rapidly if a computer program senses network problems and sequentially isolates each node until the faulty one is identified.

Network Analyzer. An insight into the real-time and past activity on an operating (or nearly operating) network, is an excellent aid in diagnosing both hardware and software problems. This fact prompted the design and construction of a network analyzer. It consists of a receive-only interface coupled to a commercial logic analyzer. This allows display of captured pre- and post-trigger information showing network activity, limited only by the internal memory of the logic analyzer.

Software

Software support for Novanet is an ongoing project and presently includes the following tasks:

1. Downline load capability through a combination of VAX software and special boot read-only-memory installed in the LSI-11 processors.

2. A PDP-11/LSI-11 stand-alone device driver for use with our Praxis coded front end processors.

3. A VAX/VMS multi-user driver for use on the main system processors.

4. A PDP-11/LSI-11, RSX-11/M driver for use on processors using the RSX operating system.

5. Network Shared Memory (NSM) which provides the user with the equivalent of multi-ported memory across network connected nodes in VAX, PDP-11 and LSI-11 processors.

6. File Transfer capability between processors using the VMS or RSX operating systems. This capability is presently under development.

Nova Target Diagnostics

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 picosecond response, photomultipliers and silicon photodiodes with 1-2 nanosecond 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 crosstalk and signal degradation.

Architecture

The Nova Target Diagnostics 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 minimized analog signal cable lengths and maximized the signal to noise ratio. All diagnostics are isolated from the target chamber, the space frame 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 the low capacitance power transformers and a single point grounding scheme.

The system will be menu controlled both for system configuration and actual operation. System configuration will be accomplished by filling out a form displayed on a CRT connected to the VAX and accessing the control database. Color graphic touch panels will be the primary operator interface in both the control room and various remote areas around the target room near diagnostic instruments. Color touch panels will be located in the diagnostic loft, the target room and the switchyard for convenient access and setup of diagnostics (see Fig. 2).

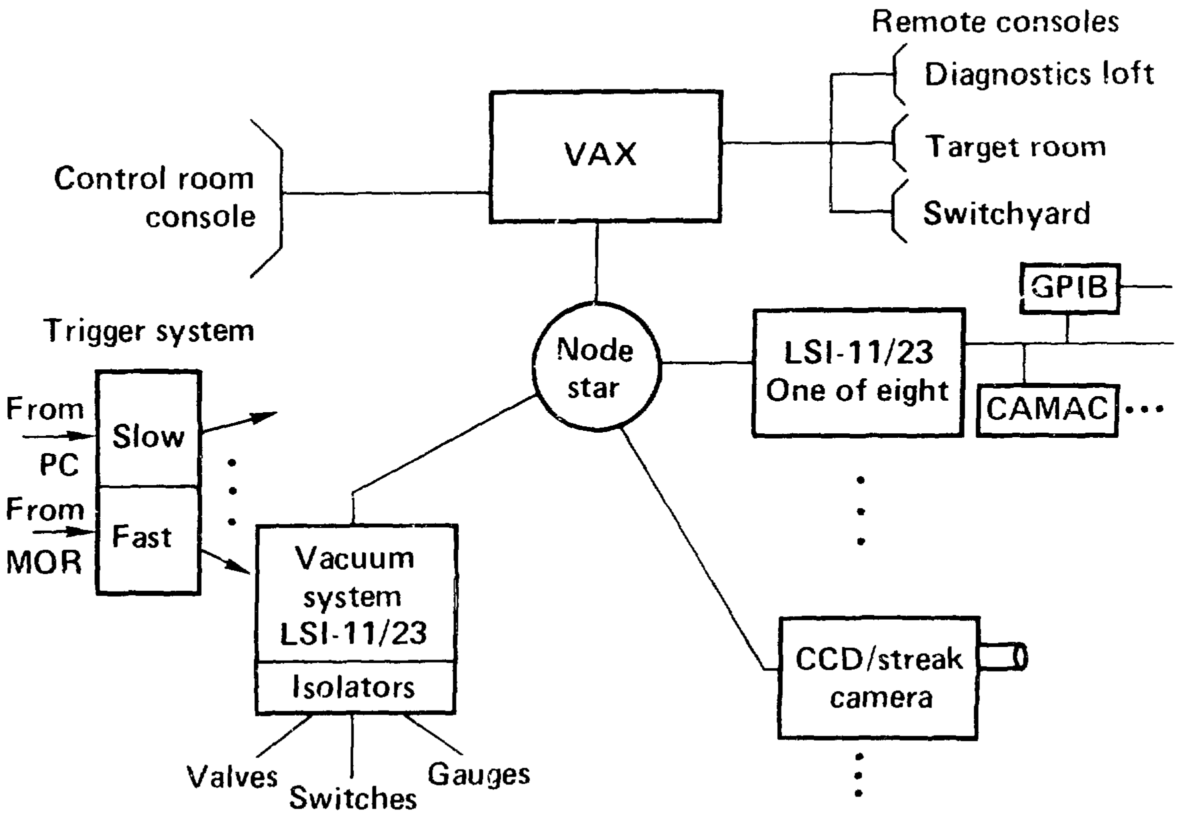

Fig. 2 - Target Diagnostics Architecture

An integrated vacuum system for both the target chamber and the individual diagnostics will be controlled and interlocked using an LSI-11 processor. Vacuum control maps of the chamber and each diagnostic will be available at any of the color graphic touch panels.

Trigger System

The trigger system for target diagnostics synchronized both the FEPs and the data digiters with the show countdown sequence. The trigger signals come from two sources (see Fig. 3). The "slow" triggers originate from the power conditioning system and inform the FEP of the state of the show sequence. The "slow" system signals are sent to an Initiator Transmitter where the option of a local dry run capability may be selected. The fiber optic output from the Initiator transmitter terminates at the Initiator Receiver in one CAMAC crate attached to each of the front end processors. The Initiator Receiver interrupts the processor at each change in the shot sequence status and therefore synchronizes each FEP to the shot countdown.

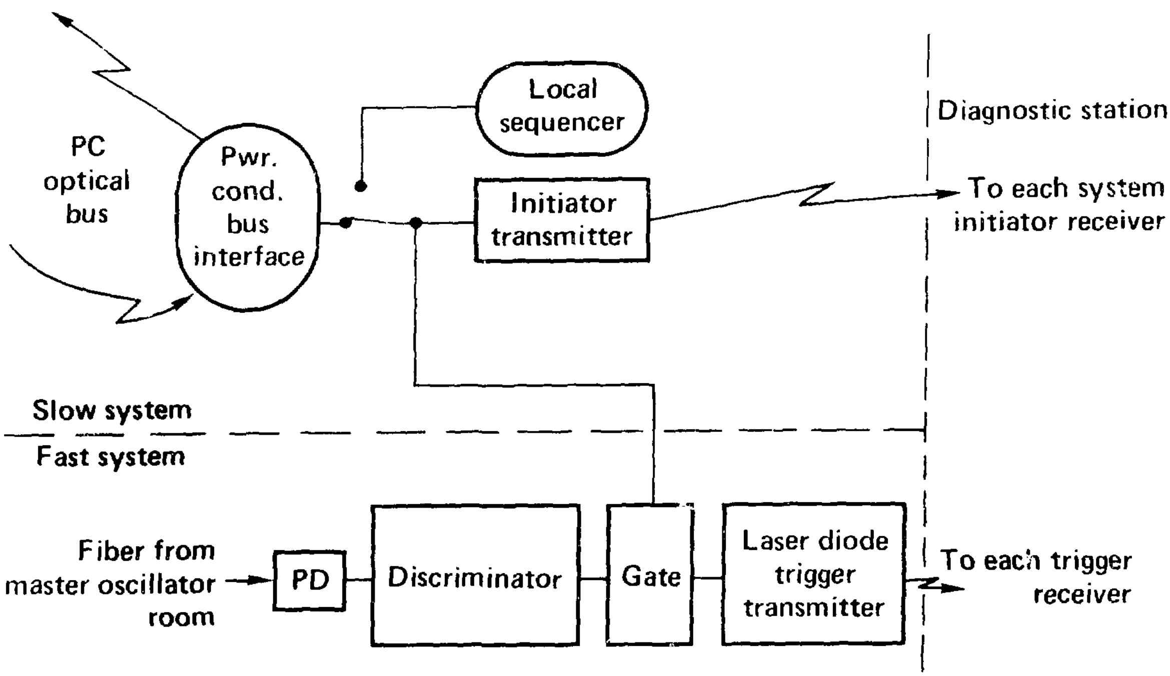

Fig. 3 - Target Diagnostics Trigger System

The "fast" trigger originates from the master oscillator where a fraction of the main laser pulse is sent to a photodiode in the diagnostic area. The photodiode's output is discriminated and gated by the slow trigger system, (to allow the fast trigger to propagate only on actual shot sequences) then converted back to a constant amplitude optical pulse by the Laser Diode Trigger Transmitter. Each FEP has a Trigger Receiver CAMAC module that interrupts the processor at show time and also converts the optical pulse back to an electricl signal for distribution to all instruments in the diagnostic station.

Diagnostic Station

A diagnostic station is defined as an electrically isolated group of racks, at least one front end processor, at least one CAMAC crate, and the digitizers and equipment required to support an associated diagnostic detector. Each diagnostic station is completely isolated using fiver optics for all inupt and output signals (except the isolated detecter) and the power is supplied through low capacitance isolation transformers. A single safety ground of heavy guage wire is connected from each station to the local common ground rod (see Fig. 4). "Daisy chaining" of this ground wire is not permitted. The fiber optic control signals from Novanet go to the Node Star in the control room.

System Philosophy

Our past experience on previous lasers has shown that the target diagnostics system must remain flexiable and allow easy changes in the hardware configuration. These previous three systems utilized .DP/LSI-11 software that kept the configuration database in the acquisition processor. This was acceptable for a time, but as the system grew, the software to control the expanded hardware and the information in the expanded database became too large for the front end processor to conveniently handle. Our software was normally written in assembly language, BASIC or FORTRAN. Software maintenance was difficult and it became impossible to add new device drivers after the original implementors left or moved to new assignments. Consequently several guidelines were established:

1. The central VAX computer is part of most control loops.

2. Minimal intelligence is required in the Front End Processors. This also means no mass storage on the FEP. Send the data to the VAX over the network.

3. Minimal configuration information exists in the FEP. Only real time control information is needed in FEP.

4. Software is written in Praxis to force strong type checking and compatibility amoung program modules, and to aid in long term software maintenance.

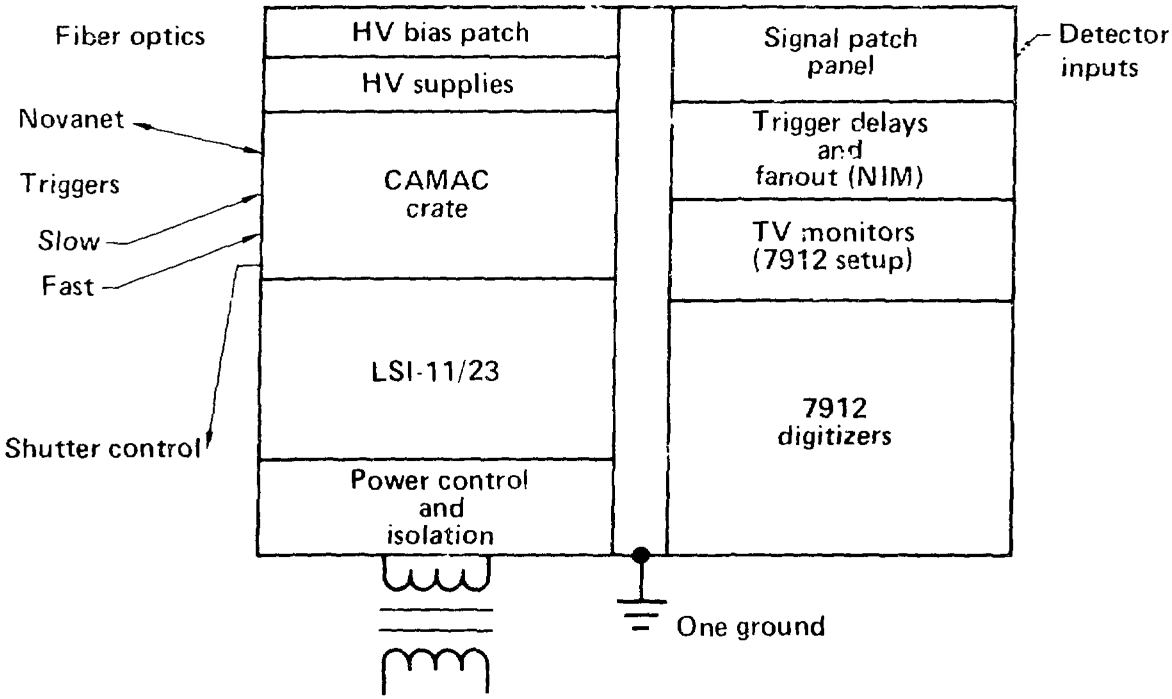

Fig. 4 - Diagnostic Station

Data Flow

The diagnostic system is a data sink, with major control functions limited to proper setup and vacuum integrity control. However, a large volume of data is acquired from devices such as the CCD streak and framing cameras, normally 160 kilobytes per shot from each camera. Calorimeter digitizers and Tektronix 7912 transient digitizers normally return between 2 and 4 kilobytes of data per shot. Following pre-shot setup, the post-shot acquisition reads all large voleme data devices sequentially into 3 raw shot data files (on disk). The small volume data devices are read and the data is stored directly in the shared memory regions in the VAX. After all devices have been read, the shared memory region is copied into the raw shot files, thus preserving both the data and the final shot configuration including diagnostic parameters that occurred on the actual shot.

Past experience has shown that a distributed processing digital control system requires a fast communication network amoung all the control loop processors. Novanet solves the communications problem while maintaining the required electrical isolation by using fiber optics as the transmission medium. The use of Novanet, CAMAC standard hardware and modern, high level programming languages allows a maintainable and expandable control and data acquisition system for the Nova laser.

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