CONF-831203-41

UCRL- 89759
PREPRINT

NOVA LASER FACILITY FOR INERTIAL CONFINEMENT FUSION

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This paper was prepared for submittal to
the 10th Symposium on Fusion Engineering
Philadelphia, Pennsylvania
December 5-9, 1983

November 30, 1983

Lawrence Livermore National Laboratory

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UCRL--89759

DE84 004190

NOVA LASER FACILITY FOR INERTIAL CONFINEMENT FUSION*

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Abstract

The NOVA laser fusion research facility, currently under construction at Lawrence Livermore National Laboratory, will provide researchers with powerful new tools for the study of nuclear weapons physics and inertial confinement fusion. The NOVA laser system consists of ten large (74 cm diameter) beams, focused and aligned precisely so that their combined energy is brought to bear for a small fraction of a second on a tiny target containing thermonuclear fuel (deuterium and tritium). The ultimate goal of the LLNL 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 military and civilian applications.

The NOVA laser consists of ten beams, capable of concentrating 100 to 150 kJ of energy (in 3 ns) and 100 to 150 TW of power (in 100 ps) on experimental targets by 1985. NOVA will also be capable of frequency converting the fundamental laser wavelength (1.05 μm) to its second (0.525 μm) or third (0.35 μm) harmonic. This additional capability (80 to 120 kJ at 0.525 μm, 40 to 70 kJ at 0.35 μm) was approved by the U.S. Department of Energy (DOE) in April 1982. These shorter wavelengths are much more favorable for ICF target physics. Current construction status of the NOVA facility, intended for completion in the autumn of 1984, will be presented.

Introduction

The inertial confinement approach to controlling thermonuclear reactions is to bring small deuterium-tritium (D-T) fuel pellets to very high temperatures and densities in such a short time that the fuel will ignite and burn before the compressed core disassembles. This approach relies upon a driver (e.g., a laser) to deliver the extremely high power, short-duration burst of energy required. At Lawrence Livermore National Laboratory, our immediate scientific objectives are the demonstration of high compression (100 to 1000 times liquid D-T density) and the exploration of the required ignition of thermonuclear burn. These achievements are necessary precursors to ultimate successful realization of the energy objectives of the program. From a technical point of view, the ignition milestone is very important.

Over the past several years, a series of increasingly powerful and energetic solid state laser systems have been built at LLNL to study the physics of ICF targets and laser-plasma interactions. NOVA is the latest in this series. The NOVA laser will consist of ten beams, capable of concentrating 100 to 150 kJ of energy (in 3 ns) and 100 to 150 TW of power (in 100 ps) on experimental targets by 1985. NOVA will also be capable of frequency converting the fundamental laser wavelength (1.05 μm) to its second (.525 μm, or green) or third (.35 μm) harmonic. This additional capability (80 - 120 kJ at .525 μm, 40 - 70 kJ at .35 μm) was approved by the Department of Energy in April, 1982. Since these shorter wavelengths are much more favorable for ICF target physics. [1] NOVA's ability to explore the region of ignition of thermonuclear burn is greatly enhanced. ("Ignition" implies density and pressure conditions such that the α-particles in the central core of the compressed fuel are trapped, thus heating the remaining (cooler) fuel.)

An artist's cutaway drawing of the NOVA layout is shown in Figure 1. The conventional construction segment of the NOVA project, the 115,000 ft.^{2} laboratory building in which the ten-beam neodymium glass laser system will be installed, was completed in June, 1982. The ten beams from the laser are brought with high reflectivity mirrors to an integrated target chamber in two opposed clusters of five beams each. Frequency conversion is accomplished with potassium dihydrogen phosphate (KDP) crystal arrays, mounted just in front of the fused silica focusing lenses on the target chamber vessel. The 60 megajoule capacitor bank which powers the flashlamps is directly below the laser. The total cost of the NOVA project will be $176M when it is completed in the Autumn of 1984.

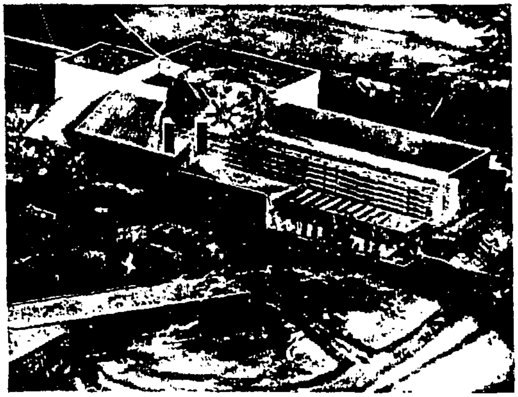

Figure 1

In this article, we shall present an overview of some of the key laser components and a discussion of frequency conversion with large aperture KDP arrays. We shall conclude with a summary of the progress made to date in installing and activating the power conditioning, alignment, diagnostics, controls and data acquisition subsystems that will comprise the integrated experimental facility. A more detailed description of these subsystems, their

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*Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48.

design and their interrelationships can be found in Reference [2].

Amplifiers

The large NOVA amplifiers feature a rectangular internal geometry that permits flashlamps to pump the laser disks efficiently. An end view of a partially assembled 46 cm rectangular amplifier is given in Figure 2. Flashlamps run along two opposing sides of the rectangular case, facing the installed disks. Each flashlamp is backed by a silver-plated crenulated reflector, which reflects light into the disk faces while minimizing absorption by neighboring flashlamps. Flat, silver-plated walls form the top and bottom sides of the optical cavity, which is very reflective and provides tight optical coupling of light from flashlamps to disks.

Figure 2

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

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, by Hoya Optics, Fremont, CA and by Schott Optical Co., Duryea, PA. A condensed table of significant optical parameters for this glass type appears in Table 1.

Table I. Optical Characteristics of Nd:Dopted Phosphate Laser Glass

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

With disks of large diameter, the gain path for internally generated amplification of spontaneous emission (ASE) becomes longer. Internal ASE represents a parasitic 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. The disks are split along their minor diameters, thus realizing much higher energy storage and gain. For NOVA, each disk half is completely surrounded by a "monolithic" edge cladding, manufactured with glass that is thermally and mechanically compatible with phosphate-based laser glass. This edge cladding serves two purposes. First, it has the same index of refraction as the laser glass, so that reflections of the internal amplified spontaneous emission that could reenter the disk and undergo further parasitic amplification are minimized. Second, because it is doped with copper ions, it strongly absorbs energy at the laser wavelength (1.05 μm), serving as a "sink" for *unwanted energy*.

Naturally, a split disk produces a split beam. Diffraction effects originating at the split are minimized by scatter plate apodization techniques.

Frequency Conversion and Target Focusing

Potassium Dihydrogen Phosphate (KDP) is one of a class insulating crystals that are suitable for frequency conversion of optical radiation. [3] KDP possesses no center of symmetry; it is uniaxially birefringent; and it is highly transparent over the entire visible spectrum. Birefringence in the current context implies that light travels through the crystal with a phase velocity that depends upon its linear polarization and propagation directions. Therefore, by properly choosing these directions, the phase velocities of two wavelengths of light (e.g., the fundamental and the second harmonic) can be matched precisely. This so-called "phase-matching" technique [4] can be used to convert light of one wavelength to its second harmonic with high efficiency - in theory, approaching 100%. It is applicable to "frequency mixing" as well.

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

KDP, in addition to its very suitable optical properties, is capable of being grown from water solution to substantial sizes. Currently, Cleveland Crystals, Cleveland, OH, and Interactive Radiation, Northvale, NJ, are under contract to produce 27 cm square crystals cut from boules such as shown in Figure 3. Growth of these boules from their seed crystals requires several months of continuous growth under carefully controlled conditions.

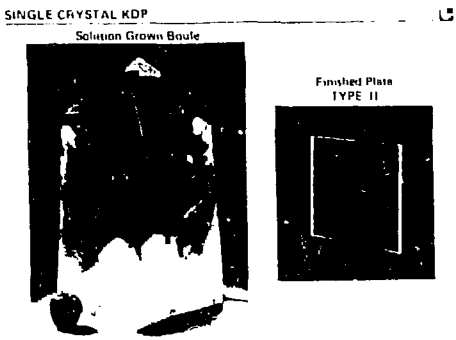

Figure 3

Once grown and rough cut, the KDP crystal surfaces must be precisely finished to exacting angular and linear tolerances. Experiments at LLNL determined that diamond turning was a feasible approach to machining of this material. KDP diamond-turning technology has currently been proven with full sized crystals, such as shown in Figure 3, which have been assembled and are currently in use as frequency doublers in the Novette laser. Cleveland Crystals, Inc. and Pneumo Precision are currently under contract to finish the NOVA KDP crystals.

Once finished, the KDP crystals are assembled into a three-by-three array, whose total clear aperture is 77 cm. The NOVA crystals will be supported in "sandwich" fashion between transparent windows of fused silica. The interfaces between KDP and silica are filled with a fluid layer to minimize reflection losses at surfaces of differing refractive index. The windows are supported internally with a set of precision finished posts located at the corners of the KDP crystals. A partial vacuum within the array assembly allows atmospheric pressure to maintain the windows snugly and evenly against the internal supports. Wavefront aberrations of the assembled array are on the order of 1 - 2 waves at 1 μm in transmission. Fused silica for the array windows and for the focus lenses is being supplied to NOVA under contracts with Corning Glass Works, Corning, NY and Heraeus Quartzschmelze, Hanau, West Germany. A prototype assembly is currently being used in Novette.

A system capable of producing both second and third harmonics over a wide range of input intensities, employing two identical crystal arrays in optical series, has been developed. [5] In this design, second harmonic generation is achieved using two Type II, 1.0 cm thick, 74 cm aperture KDP crystal arrays. 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 Figure 4a.

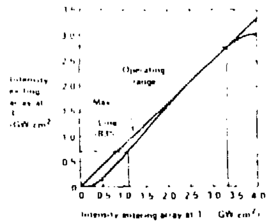

Figure 4a

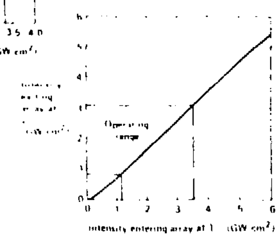

Figure 4b

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 analyzed by Craxton [6] and demonstrated by Seka, et al. [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 ($\Delta\theta$ = 6 mrad). Efficient conversion is achieved over a somewhat smaller input fundamental intensity range than for second harmonic generation. The intensity transfer function is shown in Figure 4b. The design is optimized for a fundamental drive intensity of 2.5 GW/cm^2, spanning the NOVA pulse width range of 1 - 3 ns. This operating range is consistent with other system constraints; i.e., those imposed by nonlinear propagation and by material fluence damage limits.

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

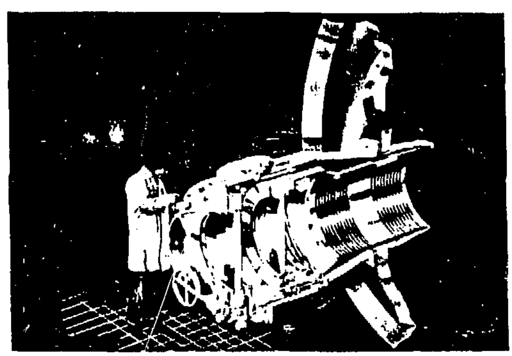

Figure 5

In Figure 5, an artist's concept of the array and focusing lens is shown, as it (conceptually) mounts to the target chamber. The focusing lens, also of fused silica, must serve as the vacuum barrier. Alignment aids (cross-hair and retro-reflector, both retractable from the beam line during shots) are also shown.

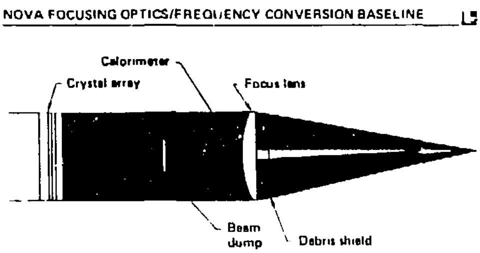

Figure 6

The optical train for frequency conversion and beam focusing is very simple; it is shown schematically in Figure 6. A dichroic beam dump (not shown in Figure 5) transmits only the wavelength desired for a particular exp iment. Dispersion in the fused silica focus lens causes different wavelengths to focus at different distances from the lens, as shown. Therefore, a target at or near the focal position for the desired wavelength lies in the shadow of the beam dump for remanent wavelengths. Care must be exercised in the placement of the crystal array relative to the focus lens to avoid having "ghost" foci (back reflections from the lens surfaces) located within the crystals. The shield is required to protect the focus lens from debris originating in the disintegration of the target itself; such debris would otherwise seriously degrade the transmission of the lens after only a few shots.

Target Chamber

Figure 7 is an artist's conception of the NOVA target chamber. The five (west) beams are equally spaced in angle upon the surface of a 100° cone whose vertex is at the target. These beams are mirrored by the east beams, so that east and west beams do not radiate into each other through a coordinate system centered at the target. The five beam overlap spot in the common focus is not expected to exceed 250 μm in diameter, including allowances for alignment, positioning, and verification tolerances.

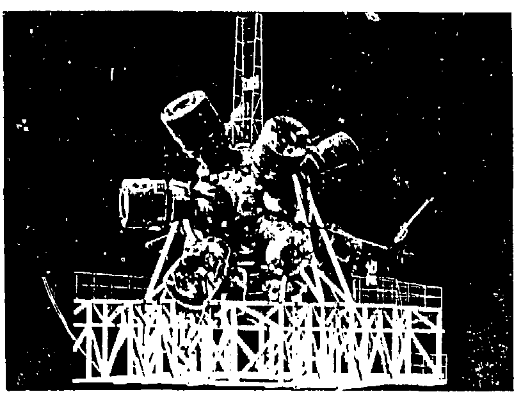

Figure 7

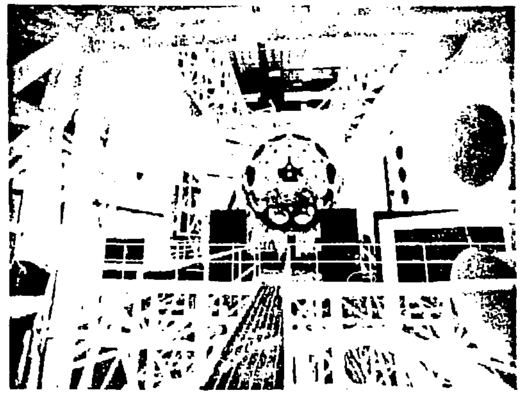

Figure 8

The NOVA target chamber, built and tested by Chicago Bridge and Iron Company, Memphis, Tennessee, is shown in Figure 8 as installed. This aluminum chamber, of 2.3 m radius, features 5 inch thick walls to accommodate component mounting without undue deflection, strain, and consequent component misalignment. Aluminum has been chosen because of its rapid recovery from radioactivity following a high yield target shot. [8]

Present Status of NOVA Construction

The laboratory and office buildings were completed in June, 1982. Installation of the tubular steel spaceframe supports for laser components, turning mirrors, output sensor packages and target chamber is complete, and installation of laser components through the 20.8 cm aperture amplifiers is well underway, as illustrated in Figure 9.

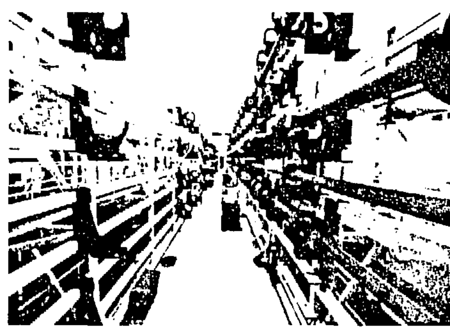

Figure 9

More than 80% of hardware procurements are currently under contract and in fabrication, and assembly of components is nearly complete. Construction of the power circuits is approximately at the 50% point. The target chamber has been fabricated, accepted as vacuum tight, and installed. Other subsystems -- alignment, laser diagnostics and controls -- are extensively deployed in support of Novette. This two-beam early version of NOVA employs NOVA hardware wherever possible; it is currently functioning as a prototype laser system, and performing selected advanced target experiments as well. The activation of Novette has proven to be an extremely valuable learning experience for the activation phase of NOVA. We confidently expect that NOVA will meet its cost, schedule and performance goals.

Acknowledgements

The lead NOVA project engineers deserve special recognition for their efforts and their professionalism: these are C. A. Hurley, Mechanical Systems; E. P. Wallerstein, Optical Components; Dr. Erlan Bliss, Alignment Systems; R. G. Ozarski, Laser Diagnostic Systems; M. A. Summers, Frequency Conversion and Target Focusing systems, F. Rienecker, Target Systems; Dr. D. Kuizenga, Oscillator and Splitter Systems; J. R. Severyn, Target Diagnostic Systems; F. Holloway, Controls; K. Whitham, Power Systems; and C. Benedix, Conventional Facilities Manager. R.O. Godwin is the NOVA Project Manager; Dr. D. R. Speck is in charge of NOVA activation. On behalf of the NOVA project, the author acknowledges the continuing support of Dr. J. L. Emmett and Dr. J. F. Holzrichter. Finally, the author acknowledges with gratitude the enthusiastic, innovative and dedicated efforts of American industry in support of this project.

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