The Novette Laser Facility: A Step in the Evolution of High-Power Laser Systems

Work with the recently dismantled Novette laser, LLNL’s flexible, high-energy-density experimental facility, has profoundly affected our understanding of laser-plasma coupling phenomena. Novette was the first in the Laboratory’s series of successively more powerful and complex laser systems to incorporate full-power harmonic conversion of laser light in nonlinear birefringent media, and with it we probed the details of the design for the Nova laser.

In the course of inertial-confinement fusion (ICF) research at LLNL, we have designed and built a series of successively more powerful and complex laser systems: Janus, Cyclops, Argus, Shiva, Novette, and soon the next generation, Nova. All of these laser systems used or will use chains of neodymium-glass amplifiers (in the form of scaled modules), and they all share the same fundamental design, called MOPA—a Master Oscillator driving a single-pass Power Amplifier. Each system in the evolving series of Laboratory lasers was designed to exploit the knowledge gained through experiments with its predecessor.

The Novette laser was the first to incorporate full-power harmonic upconversion in order to test the hypothesis that short-wavelength laser pulses couple energy more efficiently to target plasmas than longer ones do. Thus, the Novette laser provided a flexible, high-energy-density experimental facility to bridge the gap.
between the Shiva and Nova lasers, while allowing us to probe the details of the Nova design. In the late summer of 1984, its work completed, the Novette laser was dismantled and its amplifier chains were moved into the Nova laser bay.

In inertial confinement fusion, tiny but powerful thermonuclear explosions are produced by focusing a laser beam on microscopic (0.1 to 5.0 mm) deuterium-tritium (D-T) targets. Because the laser beam is very intense \((10^2\text{ to }10^4\) TW/cm\(^2\)), it generates a dense plasma where it impinges on the target material. This plasma interacts strongly with the laser beam.

As recently as 1980, opinion was still divided as to the relative effectiveness of different lasers (and laser wavelengths) as fusion drivers. Most evidence now favors a green \((0.526\text{-}\mu\text{m})\) to near-ultraviolet \((0.351\text{-}\mu\text{m})\) laser.

The Novette laser fulfilled the need for a short-wavelength source for multikilojoule target experiments. We combined components from the earlier Shiva laser, until Novette the world's most powerful, with borrowed parts delivered for the Nova laser (our 100-TW-class laser system, which reached its construction completion milestone on December 19, 1984, by firing all ten beams, frequency converted to \(0.351\mu\text{m}\), into the largest chamber).

We assembled the Novette laser on an accelerated schedule in an existing building adjacent to the new Nova laboratory. Construction began in January 1982, and the system was activated in 13 months. The facility included a Nova-style control system, the refurbished Shiva target chamber, and a full suite of target diagnostics (Fig. 1).

The Novette laser produced 18-kJ, 1-ns, infrared \((1\omega)\) pulses that were frequency doubled to green light \((2\omega)\) and focused onto targets. During 1983 and 1984, we gathered a large body of data on the performance of the Novette laser as a system. In this article, we compare calculations with measurements taken at several locations within the laser chains.

Our work with the Novette laser has profoundly affected our understanding of laser-plasma coupling phenomena. Both theoretical and experimental studies have indicated that coupling and, therefore, target performance would improve significantly when the wavelength of the incident laser light was shortened below 1 \(\mu\text{m}\). Accordingly, the Nova laser is designed for the harmonic conversion of the fundamental infrared laser pulse to green or to near-ultraviolet light before the beam is focused onto the target. The Novette laser produced these wavelengths and also, for its final ICF experimental series, the fourth-harmonic ultraviolet light \((0.263\mu\text{m})\).

**Novette Design**

Each of the Novette laser's two beam lines was optically similar to a Nova laser arm, the emerging beams having diameters of 74 cm (see Fig. 2). Harmonic conversion took place in two unique mosaic arrays of type II potassium dihydrogen phosphate (KDP) crystals. The two approximately 4.5-TW green \((2\omega)\) pulses were concentrated onto targets by two 74-cm-aperture \(f/4\) doublet lenses. Because the two pulses arrived at the target within 5 ps of each other, a typical target could be irradiated simultaneously from two sides by approximately 9 kJ in 1 ns.

We devoted about half of the Novette laser's experimental time to plasma physics studies, whose aim was to...
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Fig. 2

Each of the Novette laser's two beam lines was optically similar to a Nova arm. This optical schematic shows the relationship of the system architectures constructed at LLNL.
spatial filter lenses, which in previous laser systems were antireflection-coated with dielectric films, were replaced with optics treated by a neutral solution process. Such optics not only display excellent transmission (typically greater than 99.5%) but also have surface-damage thresholds of 12 to 16 J/cm² for 1-ns pulses, approaching those of the polished glass substrate. We tested this new technology on the large-diameter spatial-filter lenses, windows, and target-focusing lenses of the Novette laser in preparation for the Nova laser.

A major design goal for both the Novette and Nova lasers was to maximize the output energy without damaging optics. We would like to propagate an ideal beam that exactly fills the power amplifier with an output flux just below the damage limit. However, such a beam does not propagate for any useful distance without diffraction of the beam edges, which leads to constructive interference and regions of excessive optical flux. The first spatial filter in each of the Novette arms had a 2-mm-diam pinhole in its focal plane and expanded the beam from its input diameter of 2.6 to 3.75 cm. The beam profile that emerged was nearly uniform, except for six faint rings. Succeeding spatial filters re-imaged, or relayed, this beam onto the entrance lenses of the following spatial filters and eventually onto the target-chamber focusing lens. The net effect of this strategy was to achieve a measured fill-factor of 85%. This is substantially greater than the 70% or less of earlier lasers.

The MALAPROP computer code (see box on p. 18) has proven invaluable for estimating peak fluxes impinging on optical components. We used MALAPROP to calculate the electric field distribution experienced by each component during a hypothetical shot. We introduced realistic dust and damage effects into each calculation to model typical operating conditions.

MALAPROP was used to predict the ultimate performance of the Novette laser. Figure 3 summarizes the calculated capabilities of a single Novette beam. The upper curve illustrates the maximum 1.053-μm energy deliverable to the KDP array, while the lower band represents an estimate of the highest (damage limited) 0.53-μm on-target energy versus laser pulse duration.

Our designs for each amplifier stage of the laser were based on damage risk assessments made using MALAPROP computations. The components most vulnerable to laser-induced damage were the input lenses to the last two spatial filters. Neutral-solution, antireflection coatings on these optics have survived unharmed after being subjected to more than 100 shots of 1-ns duration with average fluxes of 5 to 7 J/cm² and peak fluxes twice as large. Indeed, bulk damage as a result of microscopic metallic inclusions has set the practical flux limit for these lenses.

Harmonic Conversion

The conversion of laser light into its harmonics in nonlinear birefringent media is a well-known process that was first demonstrated more than 20 years ago. Because shorter wavelengths had been shown to couple more effectively to plasmas, considerable interest arose in using this upconversion (harmonic) process to generate short-wavelength beams to irradiate fusion targets. During the last three years, efficient conversion of 1-μm light to its second, third, and fourth harmonics in KDP for beams up to 10-cm in diameter has been

Fig. 3

Performance of the Novette chain at its fundamental 1ω frequency (1.05 μm) and second harmonic 2ω (0.52 μm). The upper curve is the maximum 1.053-μm energy deliverable to the KDP array; the lower band is an estimate of the highest 0.53-μm on-target energy.
accomplished in several laboratories. Currently, material and optical coating limitations restrict the harmonic fluxes tolerable in larger, high-power laser systems. The handling and focusing of the second harmonic, 0.526-μm light, is possible with the same materials and coating technologies used for 1.053-μm light and is, therefore, relatively straightforward. At the third harmonic (0.351 μm), we are concerned with solarization of most optical glasses, low damage thresholds, and high nonlinear index of refraction.

Although solutions to these problems have been identified for the Nova laser, we were unable to apply them rapidly enough to build the Novette laser and meet an early experimental schedule. For most studies, therefore, the Novette laser was restricted to the second harmonic. We used the Novette laser to test the first Nova second- and third-harmonic converter assembly, and we designed and used a unique fourth-harmonic converter for experiments in the spring and summer of 1984, the last ICF experiments conducted with the Novette laser.

Harmonic conversion of the Novette laser’s output beams required doubler optics with diameters greater than 74 cm. To meet this requirement, the two frequency conversion arrays were mosaics of smaller crystals. Array architectures for initial operation were dictated by the size of available KDP crystals. We built one 5- by 5-element array of 15- by 15-cm crystals and another 3- by 3-element array of 27- by 27-cm crystals. The crystals and their “eggcrate” support structures were sandwiched between neutral-solution processed windows to ensure that the crystals were all oriented within a 100-μrad error cone. The fourth-harmonic converter used the same 15-cm crystals to produce green light, mounted this time in a rigid frame that also supported a second mosaic of 15-cm crystals to double the frequency once again.

Novette Operation
Near midnight on August 31, 1981, the Argus laser irradiated its last target with a pulse of green light. The next morning, we began to disassemble it, and what had been up to that time the two most powerful single-arm laser-amplifier chains ever built faded into history. By the end of September, the electrical system for the Novette laser was being installed.

Before the new year, the Shiva laser had irradiated its last target. Gradually, we removed from it and refurbished the components required for the Novette laser system. The remaining components remained in their cradles on the Shiva spaceframe until they were needed for the Nova laser.

During the summer of 1982, we began to integrate the central control system software and operation of the smaller stages of the laser. The large laser components, with optical apertures of 31.5 and 46 cm, began to arrive in August. By early September, the Novette 31.5-cm amplifier sections delivered approximately 4 TW each in separate 100-ps shots. Next, we installed the final 46-cm amplifiers and the two frequency-conversion arrays. These two 120-m optical trains had to be folded twice to fit the 70- by 15-m space previously occupied by the Argus laser.

In January 1983, we began a series of full-power, two-beam shots. On January 24, 1983, the highest powers yet recorded for a two-beam laser were achieved: 25 TW at 1ω (infrared) converted to 13 TW at 2ω (green) for 100 ps. By this time, the Novette laser was already engaged in 100-ps x-ray laser studies.

Figure 4 is a histogram of high-energy laser shots on the Novette system. Those labeled “target shots” contributed to several plasma physics investigations; those labeled “other” include all laser-system diagnostic calibrations and laser-related experiments.

The time required for cooling of the Novette output amplifiers and subsequent laser-system realignment would limit this system to about eight target shots during a 16-hour working day. In practice, however, target and target diagnostic preparation and alignment generally cut potential system usage by more than a factor of 2.
Dramatic reductions in productivity, measured by number of target shots per month, came at the beginning of an experimental sequence when an entirely new target type was first introduced. Figure 4 suggests that rates in excess of 60 target shots per month are achieved if a standard target design is used.

From March 1983 through August 1984, we successfully completed several important studies and experiments. We:
- Conducted two series of x-ray laser experiments with 100-500 ps pulses.
- Completed wavelength scaling studies using 1-ns pulses.
- Achieved densities of about 100 times liquid D-T by using targets of similar geometry.
- Completed green-target scaling studies and carried out fourth-harmonic target experiments. For these ultraviolet experiments, we constructed a new tandem 5- by 5-element mosaic array of KDP crystals. Its success influenced the Nova array design, which we subsequently tested with the Novette laser.

Essentially a user facility, the Novette system delivered energies as specified by experimenters. Delivered energy was generally within \( \pm 10\% \) of the requested value. Typically, 53 to 55\% of the infrared energy produced by each chain was converted to green light and delivered to targets. The energy delivered was limited principally by losses in lenses and debris shields that become coated with target material deposited by previous shots.

**Novette Performance**
The laser pulse that eventually reached the target emerged from Novette's actively mode-locked, Q-switched neodymium:yttrium-lithium-fluoride (Nd:YLF) oscillator as one of a train of about 20 pulses at 8-ns intervals. Each pulse exited the master oscillator with subnanosecond accuracy (\( \pm 2\% \) in energy and \( \pm 1\% \) in pulse duration) relative to the Q-switch time and was consistently selected by means of a Pockels cell gate. Future Nova experiments will require longer shaped pulses.

Triggered by the Novette computer control system, the master oscillator and preamplifier system provided all of the subnanosecond timing and trigger pulses required by the laser and target systems. In addition, the computer control system automatically measured and aligned the beam and shaped the pulses in time and space. The devices installed in the master oscillator system have provided pulses that are Gaussian shaped in time and range in duration from 100 ps to 1 ns for most target studies. Some experiments used 3-ns-long pulses, shaped to compensate for amplifier saturation, in order to produce temporally rectangular output pulses of 6 to 8 kJ.

At the preamplifier output, the single optical pulse was split into two beams whose relative timing was adjusted by means of variable-path-length sections.

**Fig. 4**
Histogram of high-energy laser shots on the Novette laser. The target shots contributed to several plasma physics investigations, and the others were laser-system diagnostic calibrations and laser-related experiments.
One of the six 46-cm output amplifiers used in Novette, each containing two split neodymium-glass disks.
Since November 1982, we have accumulated photographs of the output infrared beams presented to the second-harmonic crystal arrays at the rate of about two per day. Virtually all of these images, like the 10-TW sample shown in Fig. 7, are quite uniform in appearance, with slight evidence of nonlinear breakup. At 12 TW, small-scale, self-focusing effects are more apparent. The prominent dark shadow bisecting the image is caused by the absorbing region in the largest (46-cm) amplifier disks. Intensity-dependent modulation grows as the output power increases. Our simulations from MALAPROP indicate that 1-ns operation becomes unacceptably risky above 10 TW per beam.

Table 1  Amplifier gains measured as each amplifier was installed in the Novette laser.

<table>
<thead>
<tr>
<th>Amplifier type</th>
<th>Diam, cm</th>
<th>Nominal gain</th>
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</thead>
<tbody>
<tr>
<td>Rod</td>
<td>5.0</td>
<td>25.9</td>
</tr>
<tr>
<td>Disk</td>
<td>9.2</td>
<td>6.6</td>
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<tr>
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<tr>
<td>Disk</td>
<td>46.0</td>
<td>1.8</td>
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Fig. 6  Measured Novette infrared output energies at the inputs to the Novette laser's second-harmonic converters for two pulse durations (a) 0.1 ns and (b) 1 ns. Data points are shown for experiments with the north and south beams of the laser. The solid curves indicate the calculated saturation of the amplifier.

Fig. 7  Output beam profile of a 10-kJ, 10-TW pulse presented to the second-harmonic KDP crystal arrays. The images are uniform in appearance, with slight evidence of nonlinear breakup. The prominent dark shadow bisecting the image is caused by an absorbing stripe along the minor axis of the 46-cm amplifier disk. The cross-hatch stripe is the band over which we scanned the image to make the profile.
MALAPROP

The MALAPROP computer code models the propagation of laser light. Using it primarily as a design analysis tool for high-energy, inertial-confinement fusion (ICF) laser systems, we have been able to account in a quantitative manner for nonlinear optics effects, diffraction, and noise sources. The code has been instrumental in optimizing performance versus cost in the design process of the Novette and Nova laser systems.

MALAPROP contains 13,000 lines of FORTRAN and is our major program for analyzing laser systems. We also have auxiliary programs to calculate some input parameters and summarize results. Analysis of a laser system such as Nova uses about 15 minutes of Cray 1 computer time and 650,000 (64-bit) words of memory.

MALAPROP simulates coherent light propagation. Its routines, or sets of routines, model all of the components contained in an ICF laser system.

Generally, it models one time slice of a light beam of a single wavelength. A cross section of the beam is spread across a fixed mesh as complex values representing intensity and phase. As the beam propagates through components in the modeled system, the intensity-phase values change to include the effects of the components. Specific components modeled include free-space propagation, apertures, noise sources, amplifiers, lenses, and spatial filters. MALAPROP uses well-tested approximations, and we have validated its simulations in many experimental situations.

The major specialty of MALAPROP is the coupling of nonlinear optics effects and diffraction, together with appropriate noise sources. At the high intensities of ICF systems, self-focusing of small perturbations frequently limits the maximum performance of the system. (Self-focusing occurs when the light beam is focused toward a narrow spot and thus becomes more intense; this can damage some optics.) By modeling these effects, system designers often avoid reducing the performance of the system and therefore reduce costs without degradation of beam quality.

We have modeled several laser systems with MALAPROP. A. J. Glass first conceived the code in the mid-1970s as a tool to help understand results of complex nonlinear physics. However, as its capability expanded, particularly to include two-dimensional effects and realistic noise sources (under the direction of W. W. Simmons), it became useful for design analysis. With it, we have predicted the impact on system performance of changes in the original designs of the Novette and Nova lasers. We have predicted which components are threatened by the laser beam, and have identified the causes for the threat. For example, when the Shiva laser became operational, MALAPROP isolated the cause of damage to the final focusing optics. It then indicated that an additional spatial filter would solve the problem. It also successfully modeled the Argus system and the since-proven advantages of its upgrade.
approach from opposite directions. Before entering the lenses that focus the pulses on the target, each beam passed through an apodizer plate, the mosaic of KDP crystals, and an infrared beam dump. Bead-blasted bands on the apodizer plate softly shadowed the low-damage threshold interstices between crystals in the second-harmonic generation array, which was located 1 m downstream. By preventing diffraction from uncontrolled phase discontinuities between KDP crystals, this technique also shields the final focusing lenses from potentially damaging intensity ripples, but at a cost of 10 to 15% of the beam area.

Almost every shot yielded a measurement of the second-harmonic conversion efficiency, and some of these data are plotted in Fig. 8. We have seen KDP frequency-conversion array efficiencies, corrected for beam area, of more than 75% for incident infrared intensities of 2 GW/cm². The theoretical curve shown in Fig. 8 was calculated for a single 1.8-cm-thick, type II KDP crystal detuned in angle less than 100 μrad and presented with an infrared beam having the same intensity spread as the Novette laser’s. By this measure, the mosaic is behaving as if it were a single crystal. If second-harmonic irradiation was desired, the beam was next passed through a filter or “beam dump,” which absorbed 99% of the remaining infrared light and passed 96% of the (green) energy.

If a fourth-harmonic pulse was needed, the green beam was frequency doubled again in an array of 0.8-cm-thick type I KDP crystals. Figure 9 shows that the Novette laser was able to deliver about 1.5 kJ of 0.26-μm radiation to targets in pulses slightly shorter than 1 ns.

The converted light from each beam proceeded through f/4 focusing lenses, which concentrated it on the targets. Most target designs called for a focal region between 200 μm and 1 mm in diameter.

X-ray laser experiments conducted on the Novette system required line foci 100 μm by 1 cm precisely oriented with respect to the x-ray laser diagnostics. To meet this request, we devised weak cylindrical lenses and installed them beyond the f/4 lenses within the evacuated target chamber. The final optical component traversed by the laser beam on its way to the target was a glass or fused silica shield that protected the lens assembly from most of the target debris. Although these shields were replaced several times during the laser’s operating life, they were coated rapidly by debris from the massive targets irradiated and typically had transmissions of only about 80%. Routine monitoring of these optics allowed system operators to adjust output and meet the needs of the experiments.

**Fig. 8**
Measurement of the second-harmonic conversion efficiency compared to the theoretical curve calculated for a single 1.8-cm-thick, type II KDP crystal. The bar indicates the spread of intensities in the laser beams, that is, the percentage of the total laser power that was delivered to the second-harmonic array at an intensity below the indicated value. For example, 80% of the total power is below the 80% point on the bar.

**Fig. 9**
The Novette laser delivered about 1.5 kJ of fourth-harmonic (0.26-μm) energy to the targets in pulses slightly shorter than 1 ns. The error bars represent uncertainties in measurements based on analysis of instruments.
Summary

The Novette laser system was the latest embodiment of the rapid evolution of powerful ICF laser systems. (The relative energies of LLNL systems from Janus to Nova are shown in Fig. 10.) Each of its two relatively compact arms exceeded the total output of all of the Shiva laser’s 20 arms. The Novette system was assembled in 30% of the time required to build the Shiva laser and achieved a shot rate on target exceeding that of the Shiva system. An evolutionary step of this magnitude in so short a time approaches a revolution in high-power laser technology. The Novette laser completed the ICF experiments planned for it, delivering up to 9 kJ of 0.53-μm light to a fusion target in 1 ns.

As a test bed for the Nova laser, the Novette laser provided the first operational experience with many new technologies:

- Segmented laser-disk amplifiers, which can be scaled to almost arbitrarily large apertures.
- Neutral-solution antireflection coatings on laser optics, which have moved the nominal damage threshold from 3–5 J/cm² to 15 J/cm² in 1 ns.
- Nova-style digital control and diagnostic techniques (fiber-optically coupled together) that can be made to work routinely by achieving up to six full-power shots in a single day.
- Large-aperture, multi-element KDP crystal arrays used to demonstrate conversion to the second, third, and fourth harmonics and to conduct target experiments with second- and fourth-harmonic energy.

Key Words: computer code—MALAPROP; inertial confinement fusion (ICF); laser—Argus, Cyclops, Janus, Shiva, Novette, Nova; neodymium-glass amplifier.

Notes and References