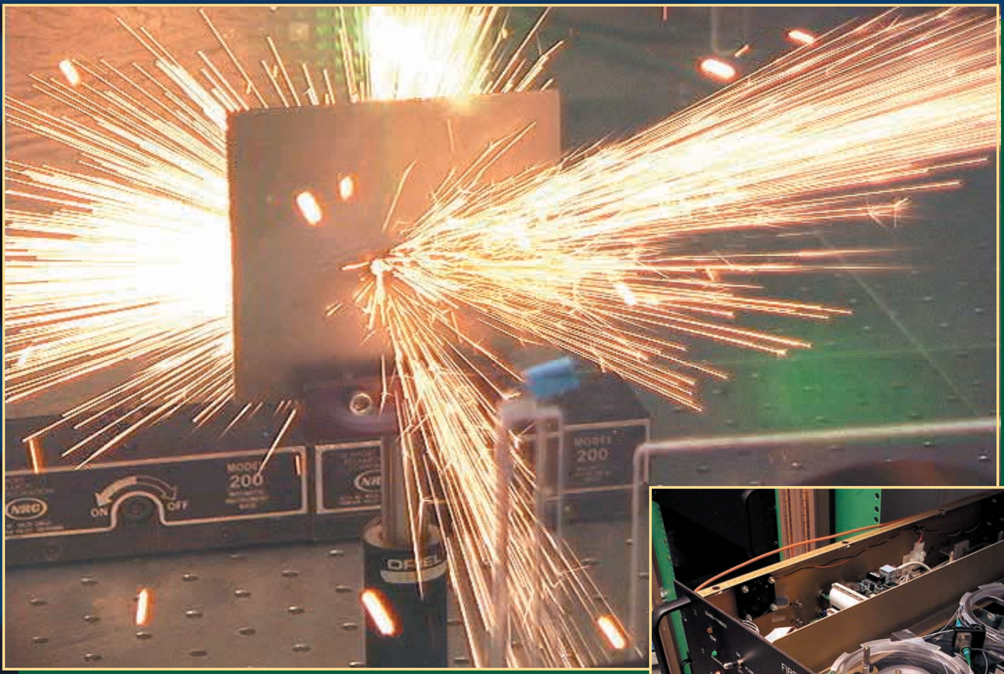
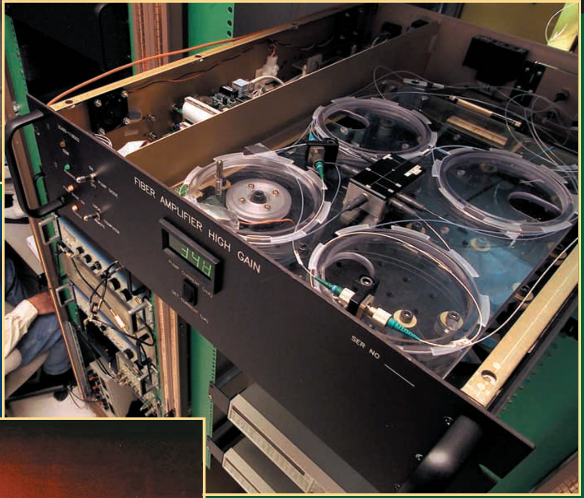
Laser Science and Technology Update – 2000





IN MEMORIAM

DR. HOWARD T. POWELL

Dr. Howard T. Powell, founder and first Program Leader of the Laser Science and Technology Program (LS&T), was a relentless advocate for high-average-power and high-peak-power solid-state laser development at LLNL.

He grew up in a small town in Washington State and graduated from the California Institute of Technology with a bachelor's degree in physics. He then earned a Ph.D. degree in Applied Physics at Cornell University in 1966.

Howard came to the Laboratory in 1973 to pursue work in inertial confinement fusion (ICF) and worked on gas lasers as efficient, rep-rated fusion drivers. In 1982, he moved to solve near-term matters (amplifiers, flashlamps, and pulse-power) for ICF research. In 1988, he led precision and beam-smoothing activities on Nova and started the diffractive optics effort at LLNL.

Howard founded and led the LS&T Program in 1995. During the past five years, he encouraged and led research on the Petawatt laser, average-power femtosecond laser systems, diode-pumped solid-state lasers, and large-aperture diffractive optics for fusion and defense applications.

Howard was a co-recipient of three R&D 100 awards for laser research: in 1988 for composite polymer glass-edge cladding, in 1994 for multi-layer dielectric gratings, and in 1997 for research in femtosecond laser materials processing.

He recruited young scientists and engineers from outside the Lab and worked tirelessly for federal funds to build the LS&T Programs. Howard was a great leader and mentor with high integrity and passion for science. He made an indelible mark on the Laser Programs and the Laboratory throughout his distinguished career.

LASER SCIENCE AND TECHNOLOGY UPDATE — 2000

H. T. POWELL AND H. L. CHEN

November 2000

LAWRENCE LIVERMORE NATIONAL LABORATORY
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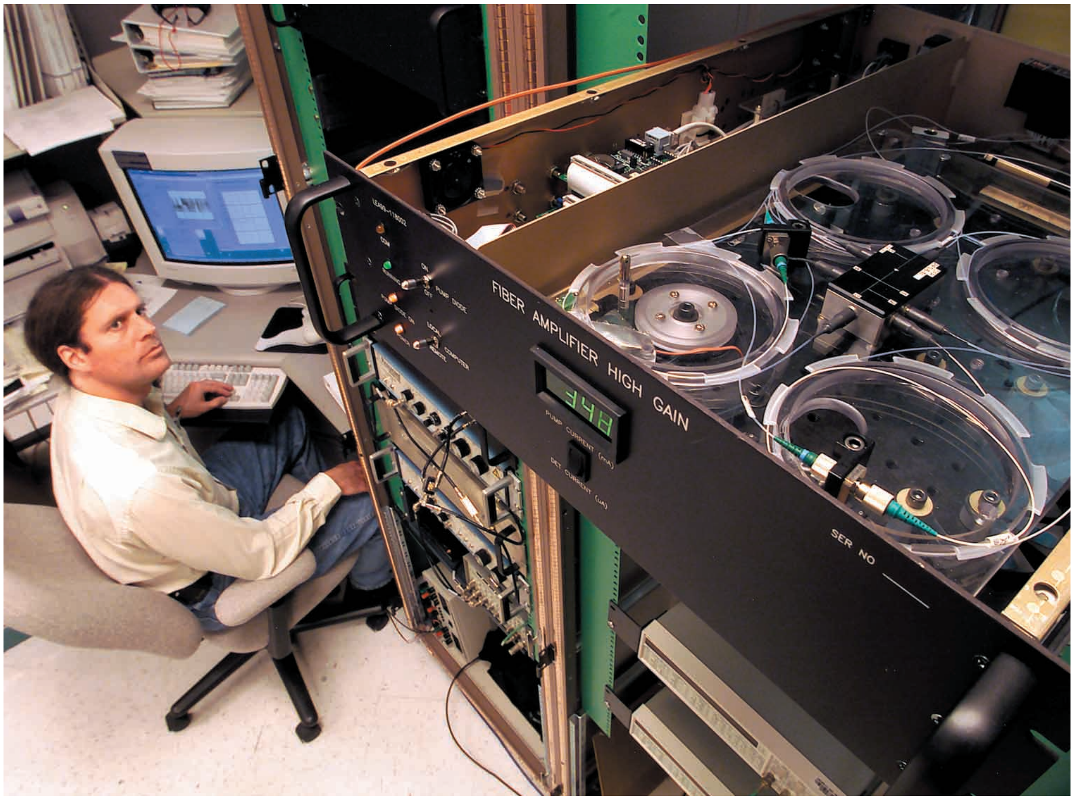


Figure 1. Fiber-optics lasers with outstanding power and wavelength stability and versatility in bandwidth and pulse shape were developed for the NIF. LS&T scientists completed the performance tests for the first-article hardware. All optical and electronic components are rack-mounted inside chassis and linked by a polarizing fiber cable.

The Laser Science and Technology Program's (LS&T's) mission is to develop advanced solid-state lasers and optics technologies for applications of national importance.

LS&T activities during FY2000 were focused on six main areas. (1) To enhance capabilities for the Department of Energy's (DOE's) Stockpile Stewardship Program (SSP), the LS&T staff focused on problem solving for the NIF final optics assembly (FOA) and on the first-article performance validation and procurement activities for the National Ignition Facility (NIF) front-end laser system. LS&T is also reconstituting a modified Beamlet laser system for use as a backlighter in Sandia National Laboratories' (SNLs') Z-pinch Facility.

(2) For the Stockpile Management Program, LS&T continued to develop an industrial-scale femtosecond laser cutting machine for DOE to disassemble weapons components and cut high explosives. (3) For the Department of Defense (DoD), LS&T continued to develop a 100-kW-class solid-state laser for lethality tests at the U.S. Army's High Energy Laser Strategic Test Facility in New Mexico and for eventual deployment in a mobile vehicle for defense against rockets, artillery, and mortars.

(4) For nuclear energy applications, LS&T began developing laser-shock peening technology to improve the service lifetime of metal canisters designed for final disposal of high-level radioactive waste and retired weapon components at Yucca Mountain, Nevada.

(5) LS&T continued developing high-average-power, diode-pumped, solid-state laser drivers for high-energy-density physics and inertial fusion energy (Mercury Project). LS&T is also developing an ultrafast x-ray source based on Thomson scattering of femtosecond laser pulses (Falcon Laser) from relativistic-electron bunches to enable studies of the ultrafast response of materials. (6) Progress continued in the diffractive optics area, where LS&T worked toward large-scale lightweight diffractive optics for the next generation of space-based optical assests (such as the proposed Eyeglass) and produce meter-scale diffration gratings for petawatt laser facilities around the world.

NIF Laser and Optics Problem Solving

Laser and optical component designs for the NIF are largely complete. The LS&T team working on the NIF has focused mainly on the first-article performance validation and procurement activities for the NIF injection laser system (ILS or NIF "front end") and on problem solving in the FOA.

The master oscillator is one of the most important subsystems in the NIF because it controls the laser's wavelength, linewidth, pulse shape, and timing. In the master oscillator room (MOR), a single laser pulse is produced and phase-modulated into 48 separate beamlines on single-mode, polarizing optical fiber. Before feeding into the entire NIF laser system, the pulses are amplified to 30 W (peak) and amplitude-modulated into high-contrast, temporally shaped pulses required for target ignition. The LS&T team, working with industry, developed a distributed feedback fiber laser as the master oscillator for the NIF. It has a continuous wave (CW) output of 20 mW at 1053 nm. Working with the NIF optics group, LS&T staff built and tested several of the MOR components, including the master oscillator, fiber amplifiers, and amplitude modulator. All optical and electronic systems are rack-mounted and linked by polarizing fiber cable. The stability of the output pulses under NIF-like environmental conditions was measured. The first-article MOR hardware successfully demonstrated the power stability (<0.5% fluctuation), gain stability (<1% variation), pulse shape (30-ns duration with >50-dB on/off extinction ratio), and wavelength stability (<1-pm) required for NIF operation.

To prolong NIF optics lifetime in the FOA, the LS&T team systematically studied the damage initiation mechanisms and measured the rate of growth of the size of the damaged region on optical components under NIF laser conditions. To achieve full performance, the NIF 3ω optics operate at an average fluence of 8 J/cm^2. At this fluence level, the durability of optical components becomes a key concern impacting the cost of NIF operation. LS&T workers identified several damage mechanisms that occurred in fused silica optics and the KDP crystals and developed a statistical model to describe empirically the onset and growth of damage sites. Photoluminescence (PL) spectroscopy and photo-thermal microscopy were used to study the creation of damage initiators. The PL measurements showed that the intensity and spectrum of photo-emission from silica are modified at damage sites. The photo-thermal measurements showed increased heating within the damage sites when illuminated with 351-nm light. It appears that laser irradiation induces bond-breaking in the fused silica resulting in "decomposition" products that are highly absorbing in the ultraviolet region. If the successive laser shots are above a threshold in fluence, the data also show that the damage continues to grow at a near-exponential rate with the number of shots. Development to mitigate both the occurrence and growth of 3ω optics damage is under way.

Modeling of all aspects of the performance of the NIF laser continued throughout this period. The existing "end-to-end" NIF model was improved and used to establish the required optical performance for various subsystems. This allowed NIF engineers to set optics specifications that will guarantee the NIF's spot-size performance. The modeling team utilized their power-spectral-density characterization of optic parts and interacted with vendors to incorporate this advanced methodology. The Laser Optics Damage Inspection system for the NIF chain was analyzed with the full 2D diffraction code, and system parameters were selected to give the highest possible performance. The "front-end" ILS simulation was improved with detailed optics interferometry data and amplifier gain information, and many layouts and component variations were analyzed to specify the beam quality as supplied to the main laser chain. The adaptive optics model was upgraded and used to set system specifications. The FOA 3ω frequency conversion design was also upgraded using LS&T frequency conversion codes, and NIF technicians determined the effects of numerous off-specification optics conditions. Reverse propagation of "speckled" beams produced by retroreflection from the target was analyzed using 2D diffraction. Analysis of ghost foci in the FOA was carried out, and optics tilts were found that minimized the problem. Finally, the 3D amplifier pump model was largely completed and compared to Amplifier Module Prototype Laboratory (AMPLAB) data, and the results were used to predict the gain in the NIF large amplifiers. The gain values were used in mission performance and power balance calculations.

Construction of the Z-Beamlet at Sandia National Laboratories (SNL)

Under the auspices of DOE's Inertial Confinement Fusion (ICF) Program, LS&T, in partnership with Sandia, is building a laser backlighter system (the Z-Beamlet) for x-ray radiography at SNL's Z-facility in Albuquerque, New Mexico. The Z-facility employs electrical pulsed power to drive a z-pinch implosion, which generates x rays to drive hig-energy-density physics experiments. In recent years, Z has produced 2 MJ of x-rays per shot at ~250 TW peak power with about 15 to 20% electrical efficiency. To reduce the cost of the laser backlighter, many optical components from LLNL's Beamlet were reused, but numerous changes to the original components were also made. These include construction of a new fiber optic seed pulse generator for the master oscillator, a picket fence pulse generator for pulse shaping 2ω transport to target, and a shock-resistant final optic assembly. Installation of the backlighter laser system in the Z-facility has begun, amplifier gain tests are under way, and beam calibration shots in the target chamber will begin in FY 2001. When completed, Z-Beamlet will generate laser pulses with up to 2-kJ energy at 2ω in a picket fence of pulses having an overall duration of ≤2 ns, with a final focus spot size ≤50 microns in diameter.

Femtosecond Laser Machining of Exotic Materials

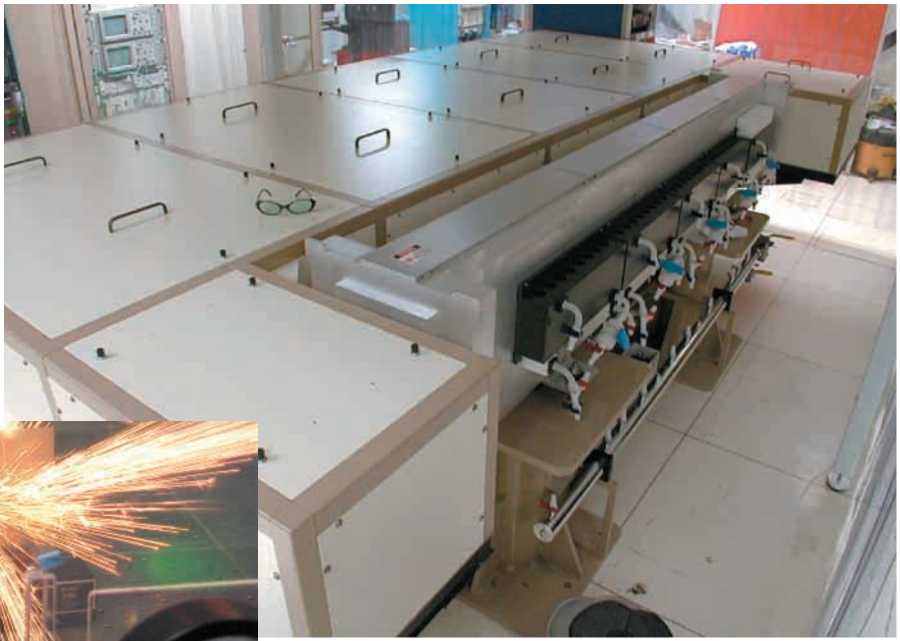
Under the support of DOE's Stockpile Management Program and DoD's Office of Munitions, LS&T developed a compact, portable femtosecond laser system for the Defense and Nuclear Technologies Directorate to be used in the High Explosives Application Facility (HEAF) to machine high explosives and energetic materials. The machine tool is powered by a Ti:sapphire laser pumped by a frequency-doubled, diode-pumped solid-state laser. It has an average output of 5 W (1.4 mJ/pulse @ 3.5 kHz with 120-fs pulse duration), with a capability to increase to 20–25 W when additional power amplifiers and pump lasers are installed. The laser system is fully automated and can be operated by personnel with little laser expertise. Anticipated mean time between maintenance for the laser system is over one year, limited mainly by the lifetime of laser diodes.

As a result of the HEAF activities, LS&T has recently demonstrated femtosecond laser machining of high explosives without burning or detonation. To determine the sensitivity of pulse duration for machining of explosives, the cutting of explosives with pulses of longer duration (500 ps) was also tested. The heat deposited by the long pulses repeatedly triggered an intense burning in the explosives. Bulk heating of the explosives by the long pulses was anticipated because the estimated electron-phonon energy transfer time is very short, typically about 10 ps. Under a work-for-others contract, LS&T has recently completed the design of a 100-W class femtosecond laser system for manufacturing.

High-Average-Power Solid-State Lasers for the Department of Defense

Under the support of the Army's Space and Missile Defense Command and in collaboration with industrial partners (Raytheon, Litton, and others), LS&T is developing a high-average-power, solid-state, heat-capacity laser technology for application in tactical short-range air defense missions. The ultimate vision is an electrically powered, diode-pumped, solid-state weapon that can be deployed on an all electric vehicle. To establish a solid technical basis for the heat capacity laser operation, LS&T built a flashlamp-pumped Nd:glass laser prototype. During the previous year, a 3-disk heat-capacity laser amplifier module was successfully operated at 10 Hz with an output of 140-J/pulse. LS&T is now constructing a 9-disk amplifier. When completed, this 9-disk module is expected to have 10-kW average output power and deliver laser pulses with beam quality <3× diffraction-limited and energy of 500-J/pulse at 20-Hz for 10-second bursts. Experiments are under way to measure gain uniformity and wavefront distortion to characterize a deformable mirror system to meet system requirements delineated to the High Energy Laser System Test Facility (HELSTF).

Using the 3-disk prototype heat-capacity laser described above, a series of target interaction demonstrations were performed. Coupons of steel, aluminum, and carbon composite were irradiated by the high-energy laser beam. During these tests, the heat-capacity laser was operated at 10 Hz with energy of 80 J per pulse. The irradiation pulse has a temporal envelope of 300 to 400 ms and consists of several relaxation-oscillation spikes with peak intensities near 2×10^7 W/cm^2. LS&T scientists successfully penetrated 2.3-mm plates of steel and aluminum after about 13 and 8 laser pulses, respectively. To guide future target interaction experiments, numerical models were developed to simulate the material removal process using one- and two-dimensional hydrodynamics codes to model the vaporization and material



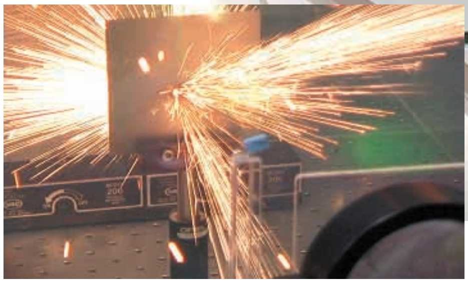


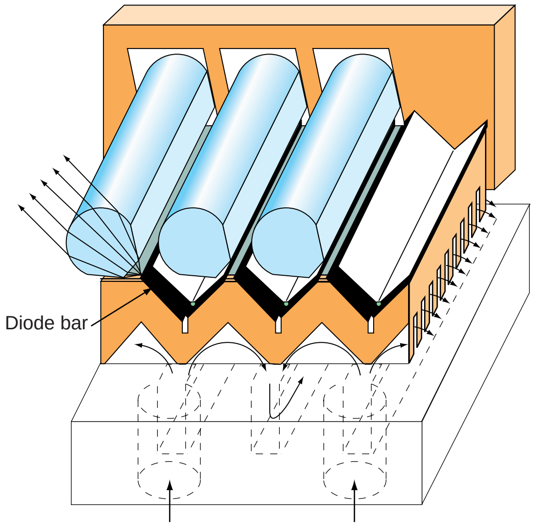
Figure 2. LS&T is developing a 100-kW diode-pumped, solid-state laser with the U.S. Army for point defense. The right photo shows a 10-kW prototype (9-disk Nd:glass amplifier pumped by flashlamps) to be in-stalled in the Army's High Energy Laser Strategic Test Facility. The photo at the left shows preliminary material removal tests made at 1.5 kW. Scientists were able to penetrate 2.3-mm plates of steel after about 13 laser pulses (140 J/pulse).

ejection process. The model predicts that the surface temperature of the target increases to 3000–4000 K during the irradiation process and that the dominant material removal process is liquid or solid ejection, rather than vaporization.

Although progress made thus far has focused on the flashlamp-pumped, heat-capacity laser, the development of a diode-pumped Nd:GGG heat-capacity amplifier testbed is proceeding. The LS&T Program has recently developed a silicon microchannel monolithic (SiMM) heatsink for high-power laser-diode arrays and successfully demonstrated output irradiance of 1 kW/cm^2 from a 10-bar diode array, as required. The thermal impedance of a SiMM heatsink is very low, ~0.35 K/W, which enables the operation of these diode arrays at high power (up to 50 W/bar CW or 150 W/bar peak at 25% duty factor) with a moderate temperature rise at the diode junction. Historically, high-average-power laser diode arrays have been difficult to produce because of the complexity of fabrication processes needed for the mounting and packaging of individual diode bars on microchannel coolers. The SiMM concept combines the advanced silicon capabilities of discrete microchannel heatsinks in a monolithic silicon cooler. It can be scaled up to high power and manufactured at low cost, facilitating a potential pathway to low-cost, high-power laser diode array manufacturing. An additional advantage of the SiMM design is that it can be fabricated with lithographic accuracy, such that the diode emission can be collimated to low angular divergence using a set of microlenses mounted in a single Si-etched lens frame.

Advanced Solid-State Lasers for Other Government Organizations and Industry

Airborne Tests of the Remote IR-Sensing System: Under the auspices of the DOE's CALIOPE program, LS&T built a high-repetition-rate, frequency-agile, solid-state laser transmitter for a differential absorption lidar system to conduct remote sensing from an airborne platform. As part of DOE's Airborne Proliferation Detection Experiment (APEX), LS&T participated in a series of remote chemical sensing tests conducted at the Nevada Test Site aboard Phillip's Laboratory's KC-135 ARGUS aircraft. The infrared (IR) lidar laser beam was generated by an optical parametric oscillator pumped by diode-pumped Nd:YAG lasers. Frequency tuning was achieved by rapid-angle tuning of the pump beam using an acoustic-optics beam deflector.



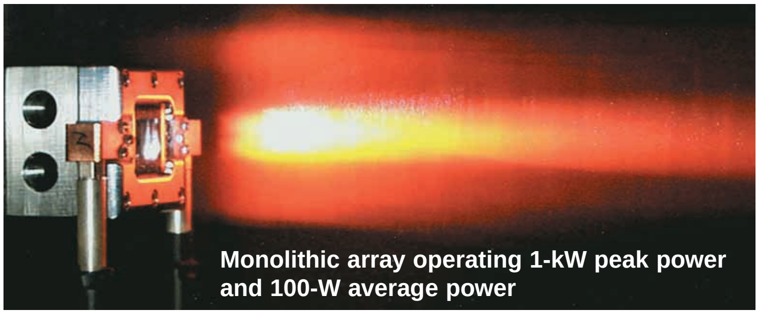


Figure 3. Efficient and low-cost laser-diode arrays are needed for the pumping of high-power, solid-state lasers. The schematic shows the configuration of the high-power diode array package using the silicon microchannel monolithic heatsink and microlens developed by LS&T.

The system had an average power of 2 W and could be repetitively pulsed at 10 kHz and tuned in the 3.2- to 3.6-μm region. After several flights, the LS&T team was able to operate this sophisticated solid-state laser transmitter reliably in the harsh airborne environment. This is a major step forward in mid-IR remote sensing.

kW-Class Diode-Pumped Yb:YAG Laser for Active Tracking: As part of a Cooperative Research and Development Agreement with Boeing Company, LS&T and Boeing jointly developed and delivered a kilowatt-class, diode-pumped Yb:YAG laser potentiality for use as a target illuminator in active tracking applications. The dual-rod laser uses an end-pumped design and a hollow lens duct to concentrate the pump light. The laser reliably produces >1 kW of CW output power with an electrical-optical efficiency of 12%, the highest output power reported to date for a Yb^{3+} laser. The laser head is very compact, with an overall volume of only 2/3 of a cubic foot. Presuming that compact power and cooling systems are developed, this kilowatt-class solid-state laser system is well suited for many military and industrial applications. To enhance beam quality, the laser resonator was specially designed to obtain a large mode size while maintaining resonator stability. The project achieved 532 W of Q-switched (at 10 kHz) output with an optical-optical efficiency of 17% and beam quality 2× diffraction-limited, the highest brightness achieved from a Yb laser to date. Boeing has subsequently improved the beam quality to be nearly diffraction-limited.

Improved Fatigue Lifetime of Metals by Laser Peening: In a collaborative effort with the Metal Improvement Co. Inc, LS&T is evaluating the effectiveness of the laser peening process in extending the service life of metal components for industrial and government applications. Using a kilowatt-class, 25 to 100 J/pulse, zig-zag Nd:glass slab laser, the team was able to induce deep compressive stresses (~2 mm) onto the surfaces of metal components to improve their service life. By optimizing the process parameters such as laser pulse duration (10 to 30 ns), fluence, intensity (100 to 300 J/cm^2), and number of treatment pulses, researchers treated a broad range of materials including aluminum, titanium, nickel, and steel-based alloys to improve component service life. Since fatigue cracks on metal components develop because of tensile stress on the surface, deep compressive stress can prevent their initiation and growth, and consequently, can improve component lifetime. Fatigue tests on 6061T6 aluminum, under various stress load conditions, showed more than 50 times improvement in fatigue lifetime for structural aluminum test plates when compared to unpeened components and 10 times when compared to mech-anically shot-peened components. LS&T is currently using laser peening to treat jet engine fan blades, gears, and hip joints. Under the support of DOE's Civilian Radio-active Waste Manage-ment System Program, LS&T is also evaluating the effectiveness of this technology to extend the service lifetime (10,000 years required!) of metal canisters designed for final disposal of high-level radioactive waste and dismantled reactor and retired weapon components potentially at Yucca Mountain in Nevada.

Average-Power Solid-State Laser Technology for Energy and Defense

Diode-Pumped Solid-State Lasers for energy and Defense, Mercury Laser: Under the support of Laboratory Directed Research and Development (LDRD) funds and the DOE Defense Programs, LS&T is building a high-repetition-rate, diode-pumped, solid-state laser (Mercury) as the first in a series of new-generation lasers for defense applications and ultimately for inertial fusion energy (IFE). Mercury is a four-pass, diode-pumped, solid-state laser (DPSSL) now in final design and initial construction. Instead of using flashlamps to pump Nd:glass, Mercury uses 45% efficient diodes to energize a Yb:S-FAP crystal gain media. Yb:S-FAP crystal has greater energy storage and better thermal conductivity than Nd:glass and can be operated at a significant repetition rate using gas cooling. When completed, Mercury is projected to deliver 100-J, 2- to 10-ns pulses (1.047-μm wavelength), at 10 Hz with 10% efficiency.

LS&T has made significant progress in crystal growth and diode array development. The Mercury laser requires Yb:S-FAP crystalline slabs of the dimension 4 × 6 × 0.75 cm. The growth of these large-size crystals has been a challenge. LS&T refined the growth procedures to reduce or eliminate the defects in the crystals and developed a diffusion bonding method to bond smaller-size optical slabs to make the required slabs. Over eighty 2.3 kW peak-power diode array tiles have also been fabricated.

Modeling of the Mercury system with adaptive optic beam improvement was carried out, and system characteristics needed to assure high beam quality were determined. A detailed system analyses was used to determine the expected cost of electricity from a future ICF power plant.

Falcon Laser Making Progress Toward Integration with Linac: Under the support of LDRD funds, LS&T is developing an ultrafast x-ray source based on Thomson scattering of femtosecond laser pulses from relativistic-electron bunches in partnership with the Physics and Advanced Technology Directorate. When completed, this capability will be used to study the ultrafast response of materials, for instance, when driven by

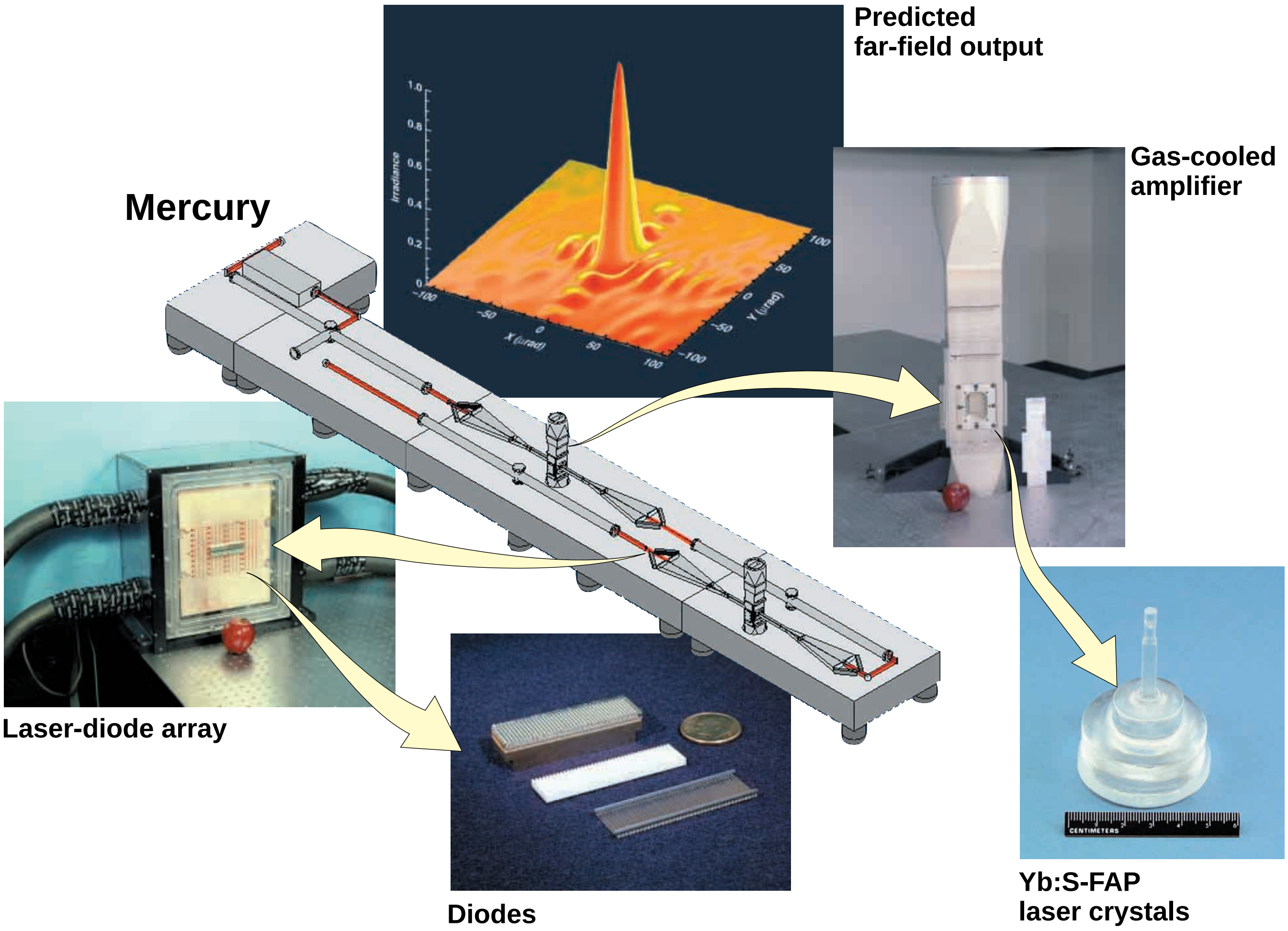


Figure 4. Mercury will demonstrate a scalable, high energy per pulse, repetitively pulsed, solid-state laser for inertial fusion energy (IFE) and defense applications. It is a four-pass solid-state laser system (based on gas-cooled, diode-pumped, crystal laser technology), now in the final assembly and testing stage.

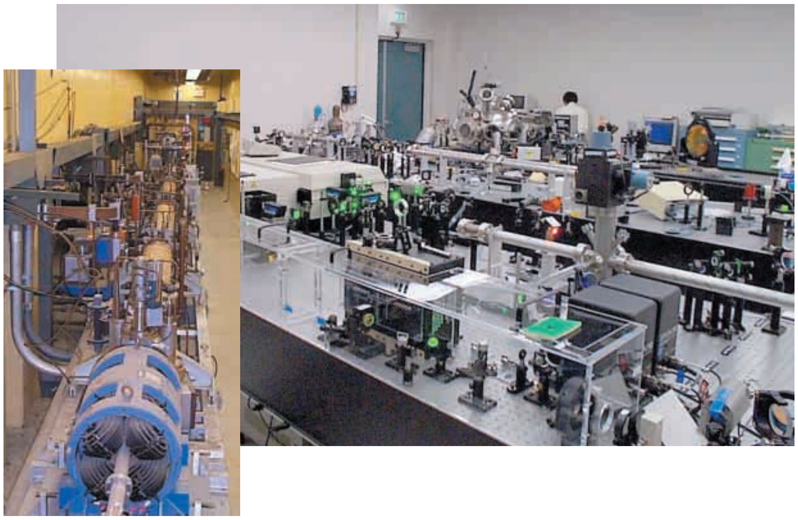


Figure 5. The Falcon Thomson Scattering Project will couple a 100-MeV electron Linac (left) with a 30-fs multiterawatt laser (right) to generate an ultrafast x-ray source for high-energy-density physics measurements.

shock waves. Femtosecond laser pulses with terawatt peak power are generated by the Falcon laser, a Ti:sapphire laser based on chirped pulse amplification. It produces 0.2-J pulses of 35-fs duration at 1 Hz and is undergoing an upgrade to the 4 J per pulse level. The relativistic-electron bunches (with 100 MeV energy) are generated in the Linac accelerator facility. Transport of the laser pulses to the Linac and integration of the two systems is under way. Precise temporal and spatial synchronization required for a Thomson scattering experiment will be demonstrated this year. Photo-electrons produced by seed pulses from the Falcon laser were accelerated to 5 MeV in a radio frequency photo-gun. Final integration of the laser beam with Linac's 100-MeV electron bunches (injected with electrons from the photo gun) will commence next year. When completed, the project expects to produce bursts of tunable hard x-rays with energy >10 keV and ultra-short pulse width <100 fs using Thomson scattering. LS&T researchers have continued to study the generation of 2.45-MeV neutrons from DD fusion by focusing the Falcon laser onto a gas jet of D_2 clusters.

Large-Scale Diffractive Optics for Space and Petawatt Applications

Lightweight Diffractive Optics for Space: Working with the Physics and Space Technology Directorate, LS&T is developing a very large-aperture (25- to 50-m) diffractive space telescope (Eyeglass) for use in space. Diffractive telescopes using Fresnel lenses fabricated on thin membranes offer several advantages over telescopes using mirrors. Thin membrane lenses are lightweight (~ 0.1 kg/m^2 areal density), packageable, and space deployable. Because they operate in transmission, their imaging is much less sensitive to surface deformations compared to the mirrors created at large size. The severe chromatic effect inherent to the diffractive lenses can be compensated for by using a relay achromatic and Fresnel corrector lens, allowing for direct broadband operation of the telescope.

As a first step in technology development, under LDRD support, LS&T built and tested a color-corrected diffractive telescope using a 50-cm-diameter, silica, f/100 Fresnel lens. The chromatic effects of a Fresnel lens were compensated for by using a relay achromatic and Fresnel corrector lens, allowing for broadband operation of the telescope. LS&T also demonstrated that Fresnel lenses can be fabricated on free-standing polymer membranes as thin as 40 μm thick.

Meter-Scale Diffraction Gratings for Petawatt Laser Facilities around the World: Following on the success of fabricating diffraction gratings used in LLNL's Petawatt Laser, LS&T fabricated over 40 large-aperture gratings (with diameter of 150 to 400 mm and 1480 to 1800 line-pairs/mm) through work-for-others contracts for institutes from France, Germany, Great Britain, Japan, and Korea. LS&T has also made gold-overcoated and ion-beam etched gratings for the National Aeronautics and Space Administration and other DOE Laboratories. The meter-scale metallic pulse compression gratings were fabricated using laser interference lithography. The diffraction efficiency of the grating is >96% at the use-wavelength and Litrow angle. The damage threshold is greater than 400 mJ/cm^2 for a 10-ps pulse. The uniformity of efficiency, typically >90%, of these gratings is also high. LS&T is currently developing all-dielectric gratings using ion-beam etching techniques for a variety of specialized applications.

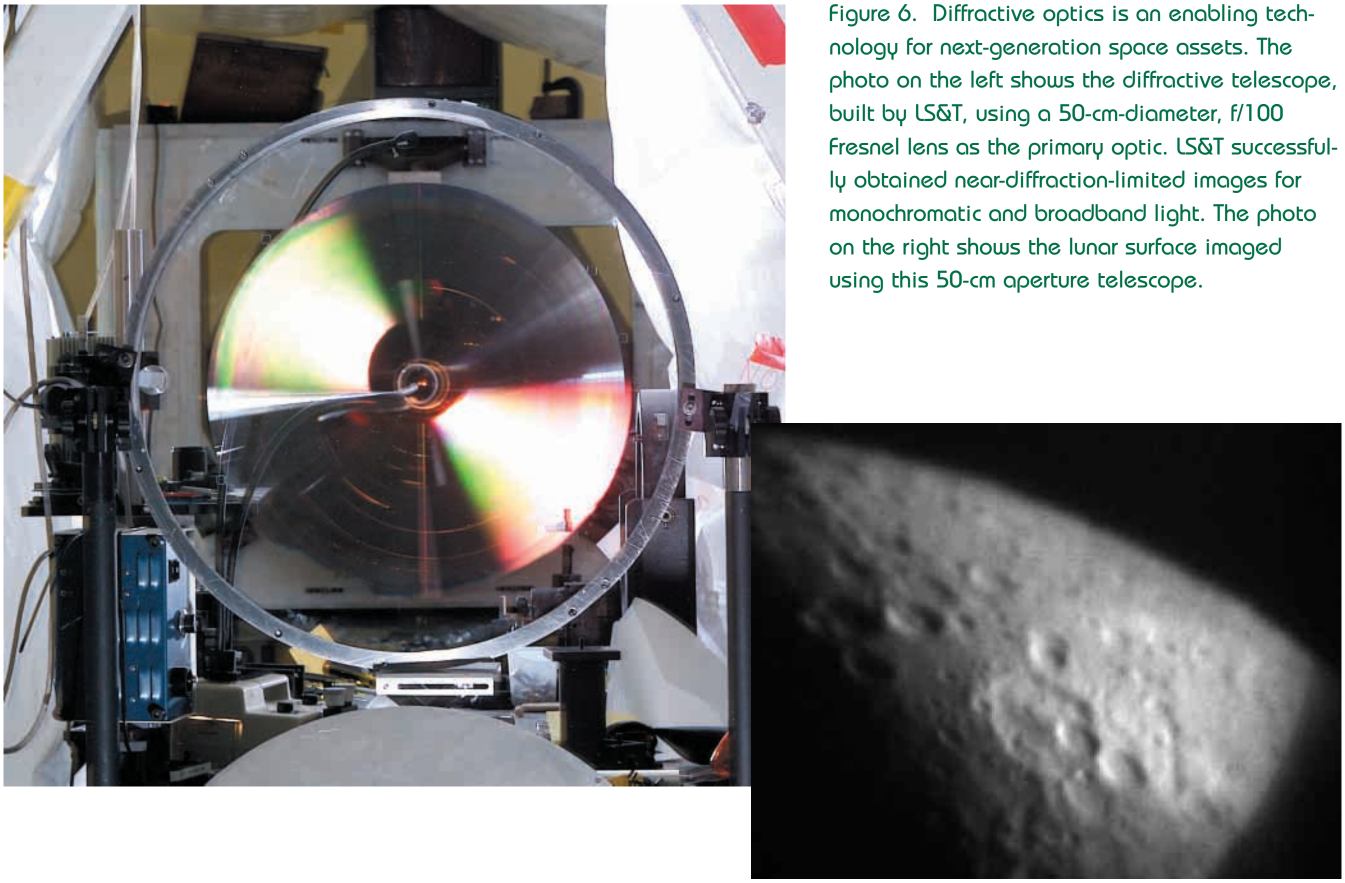


Figure 6. Diffractive optics is an enabling technology for next-generation space assets. The photo on the left shows the diffractive telescope, built by LS&T, using a 50-cm-diameter, f/100 Fresnel lens as the primary optic. LS&T successfully obtained near-diffraction-limited images for monochromatic and broadband light. The photo on the right shows the lunar surface imaged using this 50-cm aperture telescope.

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This work was performed under the auspices of the U.S. Department of Energy by University of California, Lawrence Livermore National Laboratory under Contract W-7405-ENG-48.

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November 2000

UCRL-ID-134972-00

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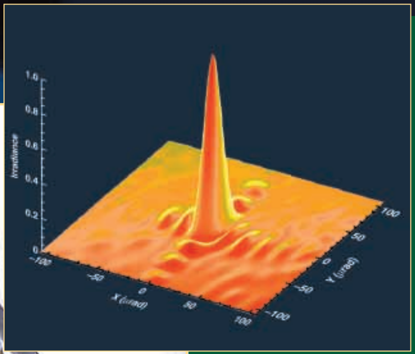

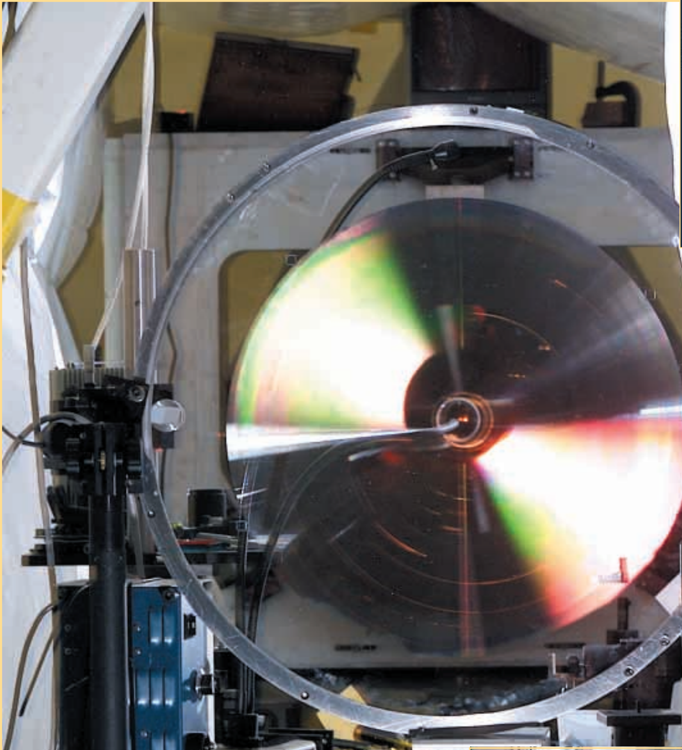

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