Laser Programs Highlights 1993

University of California
Lawrence Livermore National Laboratory
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Laser science and technology is highlighted this year by technical achievements that support the goals of the proposed National Ignition Facility, by successes in uranium enrichment technology, and by many emerging research and commercial applications for lasers.

The Laboratory is one of the world’s preeminent centers for laser science, engineering, and technology. We are applying this expertise to meet national needs in the diverse areas of energy, the environment, the economy, and defense. We also are extending our collaborations with industry and other institutions to identify laser technologies that can be developed and transferred to the private sector.

Inertial Confinement Fusion

The Inertial Confinement Fusion (ICF) Program at the Laboratory, founded in 1972, includes research on virtually every aspect of inertial-confinement fusion science and technology. In a fusion reaction, the nuclei of two lightweight atoms collide to form a heavier atom, releasing immense energy. Given equal amounts of fuel mass, the energy from fusion is about a million times greater than that released from a chemical reaction, such as the burning of fossil fuels. Our ICF approach uses intense laser light focused onto a target containing deuterium-tritium fuel. The fuel is compressed and heated to “star-like” fusion conditions of tens of millions of degrees and pressures of hundreds of billions of atmospheres.

We say that we have achieved energy gain when more fusion energy is released than the energy required to initiate the fusion reaction. Our continuing goal is to produce thermonuclear fusion gain in the laboratory with significant energy yields for defense and civilian applications.

For defense purposes, we continue to conduct many experiments with the Nova laser as a way to study the basic atomic physics, radiation, equation-of-state, and other processes that are important in understanding thermonuclear weapons. We are extending our ability to simulate the effects of nuclear weapons on hardware that must function in a nuclear environment.

In civilian applications, inertial fusion energy could eventually provide an environmentally attractive, inherently safe, and virtually inexhaustible source of energy. As our understanding of laser science and technology grows, we are finding many new ways to apply our tools and theoretical results. Our applications range from the imaging of biological specimens to theoretical insight into nuclear synthesis within stars.
The National Ignition Facility

Because we study how ICF technologies can address the country’s defense and civilian needs, many of our activities are directed by national policy.1-3 The DOE’s ICF Advisory Committee (ICFAC) is commissioned to review progress in the national ICF Program. Their recent review led the Secretary of Energy on January 15, 1993, to approve a conceptual design study for the National Ignition Facility (NIF). As currently envisioned, the NIF will consist of the next-generation, 1.8-MJ, 500-TW, 0.35-µm glass laser, with the goal of demonstrating fusion ignition and energy gain in the laboratory. (For comparison, the Nova laser produces ~120 kJ of laser energy at its infrared wavelength in a 2.5-ns pulse.) After receiving DOE approval of the mission need of the NIF, we began conceptual design activities for the facility; our goal is to complete the NIF Conceptual Design Report by the summer of 1994.

The ICFAC also revalidated the “blueprint” for the national ICF Program that was laid out by the National Academy of Sciences in their 1990 program review.1-3 This review judged that the NIF goal could indeed be achieved within a decade and recommended that this initiative be the top priority of the national ICF Program. In response, we have focused our activities in target physics and laser science to support the ignition and gain goals of the NIF.

The Nova Technical Contract defines twelve goals related to ignition physics.1 In the area of target physics, we are continuing to make progress in:

- Laser-plasma coupling; incorporating experimental data into theoretical models.
- Hohlraum energetics; experimentally demonstrating efficient laser-driven hohlraums (a hohlraum is the cylindrical geometry surrounding the actual target and is ideal for converting laser energy into x rays).
- Hohlraum symmetry; developing techniques to measure and analyze symmetry of the radiation inside the hohlraum canister.

In joint investigations with the Los Alamos National Laboratory, we have nearly completed the NIF target designs. Los Alamos has also contributed significantly to the ICF experiments on the Nova laser.

In 1993, we completed the broad-based Precision Nova effort. This work improves the experimental capability of the Nova facility to meet and diagnose the energy balance, power balance, and pointing accuracy of the laser beams needed to achieve target conditions similar to ignition implosions. The improvements associated with Precision Nova have enabled us to demonstrate markedly higher target-fuel densities, an important step in achieving ignition.

We established the Beamlet Demonstration Project two years ago to develop and prove the technology needed in the next generation of glass-laser drivers, such as the proposed NIF. The Beamlet laser is now being assembled at LLNL. In 1993, we demonstrated many advanced components of the Beamlet laser. The Beamlet milestone of 5 kJ of 0.35-µm laser light in a 3-ns pulse is set for the 1994 fiscal year.

Crucial to the success of high-power lasers like Nova and the proposed NIF is the ability to control laser-induced damage to optical components. We are using atomic force microscopy (AFM) to study how atomic-scale defects can initiate laser damage on the surface of optical components. We have shown that atomic-scale defects on graphite (carbon) initiate damage, and that defects in optical multilayers lead to catastrophic failure. We are studying defects during the growth of KDP (potassium dihydrogen phosphate), which is an essential material for frequency conversion in lasers. The deposition and growth of polymeric materials onto a substrate, also of importance for laser-

### Lasers Highlights for 1993

**Inertial Confinement Fusion**
- Began the conceptual design of the National Ignition Facility (NIF).
- Brought NIF target designs nearly to completion.
- Completed the Precision Nova effort.
- Demonstrated two-pass operation of the Beamlet laser.
- Continued progress in the Nova technical contract.

**Isotope Separation and Advanced Manufacturing**
- Completed the most important set of integrated enrichment demonstrations in AVLIS history.
- Demonstrated unique copper-laser capabilities in precision hole drilling.
- Developed and demonstrated electron-beam, cold-hearth melting and casting systems for recycling alloyed uranium.

**Advanced Applications**
- Demonstrated a tunable solid-state laser that is nearly 10% “wall-plug” efficient, about ten times better than previous such lasers.
- Developed 9-mm laser diode bars with 75 W of average power, and constructed two-dimensional arrays incorporating 300 of these devices in a 2-x 15-cm package.
- Demonstrated a diode-pumped, Q-switched, 250-W-average-power, solid-state laser oscillator; the output of this oscillator can be frequency-doubled to 100 W, a world record.
- Developed a transportable, diode-pumped, 2.9-µm erbium laser for communications through the atmosphere.
fusion target fabrication, has been studied by AFM. Moreover, we are measuring the roundness and roughness of laser-fusion spheres on the atomic scale by spinning a finished fusion sphere mounted on an air bearing under the tip of an AFM.

In one promising area of inertial-fusion energy research, we are exploring a new scenario that uses extremely high-irradiance, short-pulse lasers to ignite isotropically compressed deuterium-tritium fusion fuel. This scenario could drastically reduce costs and shorten the time required to develop fusion energy as a potential commercial process.

**ICF Technology Spinoffs**

ICF technologies continually generate new capabilities and knowledge in areas such as x-ray physics, computational physics, and diagnostic techniques. This year, for example, we received an R&D 100 Award for developing a single-shot transient digitizer. This inexpensive replacement for oscilloscopes records electrical signals as brief as 30 trillionths of a second—eight times faster than comparable systems—and has applications in high-speed physics, telecommunications, radar systems, and many other areas.

Our expertise has given rise to many multidisciplinary ICF programs for the development and application of laser technologies, such as laboratory x-ray lasers and advanced x-ray optics. Laboratory x-ray lasers are being used to image biological specimens. In proof-of-principal experiments, we produced three-dimensional, x-ray holographic images of complex test structures.

We are also collaborating with industry and other DOE facilities to launch a national program in soft-x-ray projection lithography using the advanced x-ray optics developed in our ICF work. This process is ideally suited to the manufacture of the next generation of microchips with more than a billion "transistors." Commercially developed soft-x-ray projection lithography could help the U.S. regain preeminence in microelectronics lithography.

Another important achievement in our microfabrication technology has been the development of a new type of chromatically corrected diffractive lens. Such a lens could have applications in cataract surgery as well as in optics for military use.

**Isotope Separation and Advanced Manufacturing**

Our Isotope Separation and Advanced Manufacturing (ISAM) Program has two components: Atomic Vapor Laser Isotope Separation (AVLIS), which is directed primarily toward uranium enrichment, and Advanced Manufacturing, directed toward innovative uses for AVLIS technology.

**AVLIS**

The mission of AVLIS is to provide the U.S. with a uranium-enrichment technology that can produce nuclear fuel at a cost lower than that of current technologies—gaseous diffusion and gas centrifuge. This new technology would allow this country to compete successfully in the multibillion-dollar-per-year international market for enriched uranium. We have developed and demonstrated the uranium AVLIS process so that it can be deployed by the private sector. We are completing the documentation of the AVLIS effort, and the Laboratory is in the process of overseeing the transfer of AVLIS to the U.S. Enrichment Corporation (USEC).

AVLIS hardware divides naturally into separator and laser subsystems. In the separator, an intense electron beam vaporizes uranium metal in a vacuum chamber. In the laser system, fixed-frequency copper-vapor lasers pump tunable dye lasers. Precisely tuned dye lasers selectively excite and ionize uranium-235 atoms in the vapor stream, leaving the inert uranium-238 atoms untouched. The photo-ions of uranium-235 are drawn to an electrically biased collector, producing the enriched product stream. The remaining vapor flows on through, producing the depleted tails stream. Both product and tails are continuously removed from the separator pod as flowing liquid uranium metal. The end result has been aptly described as “doing precision photophysics inside a foundry.”
**Separator Enrichment Demonstrations.** In 1992 and 1993, we completed the most important set of experiments in the AVLIS Program's history. The 15-month series of integrated enrichment demonstrations concluded with a spectacularly successful run conducted in the Uranium Demonstration System (UDS) in December 1992. In these enrichment demonstrations, a full-scale separator pod was combined for the first time with a laser system capable of illuminating all the vapor passing through it. All run objectives were met or exceeded.

The UDS was operated for 112 hours, exceeding the planned run of 100 hours. More than a metric ton of uranium was processed. More than 8000 W of power from the copper lasers pumped the dye laser chains, which operated successfully at twice their design specification. Dye laser fluence per pulse exceeded plant values. The result of these hardware successes was the production of over 150 kg of uranium enriched to an assay greater than 2%, adequate to serve as nuclear reactor fuel. Enrichment performance closely approximating that projected for an AVLIS production plant was achieved.

**Laser Demonstrations.** Between 1985 and 1993, the copper lasers in the Laser Demonstration Facility (LDF) ran 24 hours per day, 7 days per week, accumulating 2.5 million unit hours of operation. The laser amplifiers (the most stressed part of the system) demonstrated a 1200-hour mean time between failure and greater than 95% availability, both very high values for a high-power laser system. In 1992, two new chains of plant-scale amplifiers were deployed in the LDF. These lasers were designed for twice the output power of the original LDF lasers, approximately 1500 W per three-amplifier chain. After resolving typical startup problems, the two chains met a high-power demonstration milestone in August 1992, operating without failure or servicing for more than 1400 hours and generating over 2500 W (the demonstration target) for 1100 hours and over 3000 W for 300 hours.

An ongoing effort is to eliminate the chlorofluorocarbons (CFCs) that are currently used to cool electronic components in the copper laser system. Extensive changes must be made to the high-voltage power supplies and pulse-power electronics to move from a design using CFCs to one using solid-state switching and water-air cooling. We designed and built a CFC-free oscillator capable of producing over 40 W of power (compared to 20 W from the previous design); in June 1993, we completed a 200-hour high-power demonstration of this new oscillator.

During the last year, the AVLIS tunable dye lasers set new records for system and single-chain power. We are replacing the discrete optical components used to deliver copper laser light to the dye lasers with new optical-fiber delivery systems. The optical-fiber systems are safer, more reliable, and less expensive to build and maintain. In separate developments, we greatly improved two diagnostic laser systems. The cryogenically cooled titanium:sapphire laser, used for uranium vapor diagnostics,
was upgraded from a two-rod to a three-rod system, resulting in a power output of 56 W. The laser absorption monitors used for closed-loop vapor rate control were switched from continuous-wave dye lasers to tunable, external cavity diode lasers, reducing costs and increasing reliability.

The need to “thread” laser beams through a row of separator pods places stringent requirements on the beams’ spatial stability and wavefront quality. Last year saw great improvement in the AVLIS optical control systems. New closed-loop alignment controls suppress beam motions and maintain beam position on 152-mm-diameter optics to better than a millimeter over very large propagation distances. New closed-loop, controlled, deformable mirrors reduce wavefront aberrations substantially. An advanced wavefront-correction system further reduces deformable mirror costs while providing improved spatial resolution and online self-calibration.

- **Integrated Life-Test Demonstration.**
  During the integrated life-test demonstration, critical pod subsystems and many added diagnostics worked for 112 hours. This long-duration operation was greatly facilitated by closed-loop control of the vaporization rate (electron-gun system) and the separator temperature (pod heater system). We activated a new-generation separator pod design, incorporating lessons learned in the UDS demonstrations, in a series of test runs extending through the spring of 1993. Design improvements include an indirectly heated emitter in the electron beam gun, improved electron-beam transport that gives better protection to the guns, simplified and corrosion-resistant casters for product and tails removal, and simplified liquid containment and thermal control enclosures. The result is a more reliable pod that contains fewer parts, costs less, and is easier to refurbish. In May 1993, we operated a side-throw pod to process record quantities of uranium.

**Advanced Manufacturing**

The Advanced Manufacturing component of our program embraces several disciplines in which world-class technology developed at LLNL is applied to other problems. The most prominent of these efforts is in laser materials processing. We are applying the beams from our copper lasers, dye lasers, and diode-pumped solid-state lasers to manufacturing processes, such as hole drilling, welding, cutting, surface treatment, and high-energy synthesis. We are showing, time and again, that these lasers are better than existing techniques in both precision and speed.

In 1993, we substantially improved the beam quality of the copper lasers used in laser materials processing. The improved beams give us unique capabilities in precision hole drilling, allowing us to fabricate holes as small as 20 μm in diameter with depth-to-width ratios as high as 50:1 and very small (micrometer scale) heat-affected zones. This kind of result makes laser drilling a speedier alternative to electrode-discharge machining.

In a separate activity, we are applying a derivative technology for industrial use. Our extensive experience in the vaporization, corrosion-resistant containment, and chemical processing of actinides is being tapped in the DOE’s reconfiguration of the weapons complex.
For example, we are helping to develop electron-beam, cold-hearth melting and casting systems to recycle alloyed uranium and reduce the waste stream. These and other environmental restoration and waste management efforts are discussed in the Environment article beginning on p. 10.

**Advanced Applications**

We are developing lasers for a wide range of energy, military, and commercial uses and have technology-transfer projects with several major U.S. companies. In 1993, we made important developments in three principal areas:

- Solid-state laser and electro-optic technology.
- Imaging and signal processing.
- Charged-particle-beam and accelerator technology.

State-of-the-art lasers have applications ranging from remote sensing and medical diagnostics to manufacturing flat-panel displays or electronic circuits with submicrometer-size features. New lasers can also be used for mine detection in the open ocean, satellite communications and imaging, theater missile defense, and materials processing. Our goal is to develop semiconductor lasers and solid-state lasers of unparalleled performance for each of these applications. To further these developments, we maintain active areas of research in semiconductor laser crystal growth, processing, and packaging; insulator laser crystal growth and packaging; nonlinear materials characterization; phase conjugation; laser systems integration; micro-optics; and remote sensing.

Our Imaging and Detection Program is a multiproject effort addressing a wide range of activities. This effort encompasses advanced imaging concepts, remote sensing, signal processing and detection, and novel airborne platforms for conducting experiments. Our largest imaging and detection project is in radar ocean imaging, funded at approximately $10 million per year by the Office of the Secretary of Defense. We are developing advanced radar and signal-processing systems for remote sensing of the sea surface. In particular, we are working to develop the systems and technologies needed to detect surface manifestations of underwater phenomena using both real and synthetic aperture radars.

Other imaging and detection projects include the design and demonstration of a novel tandem-balloon system for conducting remote sensing experiments from high-altitude balloons, development of unmanned air vehicles for various remote-sensing and scientific experiments at high altitudes, and research into signal processing, data fusion, wideband radars, and image-reconstruction techniques.

We have also continued our research on high-power, short-pulse, free-electron lasers and relativistic klystrons driven by linear induction accelerators. These devices are potential power sources for future linear colliders, which would be several kilometers in length.

High conversion efficiency of electron beam energy to microwave energy can be achieved in two-beam accelerators using reacceleration of the bunched drive beam. To study the two-beam designs, we have assembled an experiment in which the modulated beam’s energy is boosted as it passes through several induction accelerator cells. In 1993, we increased the drive beam energy to 5 MeV and tested a new version of the modulator. We achieved microwave power levels of 200 MW in a single output section in these experiments. This result is within a factor of two of the ultimate goal. Such results can lead to a three- to fivefold reduction in the length of the linear accelerator.

**LLNL-Russian Collaboration**

In November 1992, the U.S., Japan, Russia, and the European Community agreed to establish an International Science and Technology Center (ISTC) in Moscow. The ISTC will give Russian scientists and engineers opportunities to apply their talents to civilian or international interest. The ISTC agreement was provisionally ratified in December 1993. Selection of the projects to be funded is scheduled for early 1994. However, the ISTC has begun to solicit and process proposals. Two Laboratory staff members representing the DOE have already worked at the ISTC, and 20 some project proposals include LLNL scientists as collaborators.
We have also initiated joint research projects with 16 Russian institutes. Our Advanced Laser Technology Program has engaged these institutes in a broad range of research projects in solid-state laser technology and remote sensing. This is the largest joint U.S.–Russian program, in terms of numbers of institutes and level of support, sponsored by any organization within the DOD or DOE.

Laser Guide Star

There are dozens of major Earth-based astronomical observatories that can benefit from the kinds of corrections that computers and lasers can combine to supply. Our Laser Guide Star has demonstrated that these capabilities are real.

Atmospheric turbulence severely degrades the resolution of ground-based telescopes. In principle, a technology called adaptive optics can remove most of the blurring by measuring the turbulence hundreds of times a second and making corrections through a deformable mirror behind the telescope’s main mirror. However, too few stars are bright enough at many observing wavelengths to be natural references for measuring turbulence, so we need an artificial reference source.

To create a guide star, we tune the LLNL atomic vapor laser isotope separation (AVLIS) lasers to 589 nm, the resonance frequency of atmospheric sodium atoms, and transport the light by underground pipe to the laser guide star’s optical site, where it is directed into the atmosphere. We then measure the characteristics of the resulting emission of the atmospheric sodium layer at an altitude of 95–105 km. We measure spot size, brightness, and stability of the emission as a function of laser power from 7 to 1100 W. Brightness is particularly important, as it determines the accuracy with which atmospheric turbulence can be measured. The measured brightness at 1100 W agrees with our computational models for the atomic physics of the atmospheric sodium layer.

This year, to demonstrate that the sodium-layer laser guide star is adequate for an adaptive-optics reference, we used a high-speed sensor to compare the wavefront measured using the laser guide star with that measured using a natural star. The two spectra were similar, giving us confidence that sodium-layer laser guide stars are indeed feasible for adaptive-optics systems at large (3- to 4-m) ground-based telescopes using modest laser power (10–20 W).

Summary

Over the last two decades, the scope of our laser research has grown immensely. The small, low-power laser systems of our early days have given way to laser systems of record-breaking size and power. Now we are focusing our activities within the target physics and laser science programs to support the ignition and gain goals of the proposed glass-laser National Ignition Facility. In our laser isotope separation work, we completed the most important set of experiments in the history of the AVLIS Program in 1993, which culminated in a spectacularly successful run that met or exceeded all our objectives. We are also developing lasers and laser-related technologies for a variety of energy, commercial, and defense uses.

On the horizon are transfers of important technologies for waste treatment, x-ray lithography, communications and security, optical imaging, and remote sensing, among others.

References

For further information contact E. Michael Campbell or Donald L. Correll (510) 423-9051.
Awards

Laser Programs people distinguished themselves for outstanding achievements in science and technology.


Edward Teller Medal

LNL has a long-standing reputation for excellence earned, in part, through the efforts of its award-winning scientists, researchers, and support staff. Again this year, many of the Laboratory’s people were the recipients of honors, and others were elected to special positions in scientific societies.

Edward Teller Medal

The Teller Medal, first awarded in 1991 at the International Conference on Laser Interactions and Related Plasma Phenomena, commemorates the achievements in fusion energy of Laboratory Director Emeritus Edward Teller. More specifically, this medal honors pioneering research and leadership in the use of lasers and ion particle beams to produce high-energy-density matter for scientific research and for controlled thermonuclear fusion. On October 26, 1993, Laboratory physicist John D. Lindl, a deputy program leader for the Inertial Confinement Fusion (ICF) Program, received the Teller Medal in recognition of his research. Lindl’s work spans a wide range of topics, including high-gain target design, hydrodynamic instabilities in ICF, implosion symmetry and hohlraums, and the physics of compression and ignition. Lindl, who joined the Laboratory in 1972, is currently the leader of the ICF Target Physics Program and is responsible for a collaborative program between LLNL and Lawrence Berkeley Laboratory to develop induction accelerators for ICF applications.

Fellows

At its annual meeting in Seattle, the American Physical Society (APS) announced the election of Richard A. London to fellowship. London, Associate X-Division Leader for Advanced Technology and member of the APS Division of Plasma Physics, was recognized for his landmark contributions to the physics of x-ray lasers and other work “including elegant and useful models of target evolution, beam propagation, and coherence.” Election to fellowship was described by X-Division Leader Mordecai D. Rosen as “special recognition for special people.” According to Rosen, London’s work in determining the optical wavelength for biological holography or taking a picture inside a cell “turned conventional wisdom on its head.”

Barry L. Freitas, Raymond J. Beach, and William J. Benett (left to right), co-winners of a 1993 R&D 100 award.
William F. Krupke and John R. Murray were named fellows of the Optical Society of America. Of the 12,000 members of this society, 935 are fellows. Krupke is Deputy Associate Director for Laser and Environmental Programs, and Murray is a senior scientist.

R&D 100 Awards

The goal of taking scientific innovations and turning them into new and improved products has been pursued at the Laboratory for over four decades and is also recognized by private industry. Each year, R&D Magazine selects 100 outstanding achievements in science and technology and honors the individuals responsible for them with the R&D 100 award. Since 1978, the Laboratory has won 50 of these awards.

Two R&D 100 awards were presented to Laser Program researchers in 1993. William J. Benett, Barry L. Freitas, and Raymond J. Beach were recognized for creating a cooling system that allows lasers to be operated at five times greater power than was previously possible. Their modular, high-power, laser-diode array is a revolutionary jump in the packaging of lasers. The array is about seven times lower in cost than competing cooling technologies.

Thomas E. McEwan and Joseph D. Kilkenny received their award for a system that electronically records electrical signals as short as 30 trillionths of a second. Their single-shot transient digitizer has applications in high-speed physics, telecommunications, and testing high-speed digital computer chips. It uses low-cost, off-the-shelf components and is an inexpensive replacement for oscilloscopes.

Award Highlights for 1993

Edward Teller Medal
- John D. Lindl

Fellows
- Richard A. London (American Physical Society)
- William F. Krupke (Optical Society of America)
- John R. Murray (Optical Society of America)

R&D 100 Awards
- William J. Benett, Raymond J. Beach, and Barry L. Freitas
- Thomas E. McEwan and Joseph D. Kilkenny