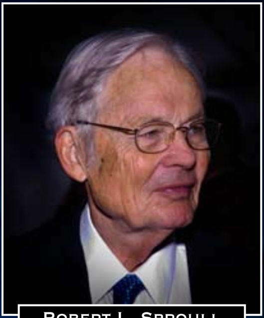
DOE/NA/28302-992
January 2011

UR LLE 40

Years of Excellence

1970 – 2010

Robert L. McCrory
LLE Director, 1983–Present



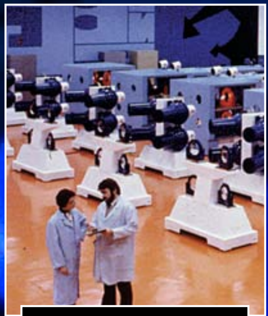
Robert L. Sproull
University of Rochester
President Emeritus

Donald K. Hess
University of Rochester
Vice President Emeritus

Moshe J. Lubin
LLE Founding Director
1970–1981

Jay M. Eastman
LLE Director, 1981–1982

ZETA Laser
1978



OMEGA 24-Beam Laser
1980

OMEGA EP Laser
2008

OMEGA 60-Beam Laser
1995

Omega Laser Facility
2008

Cover Photos

Top (left to right): Moshe J. Lubin, the founding director of the Laboratory; Robert L. Sproull, University of Rochester President at the time of the Laboratory's founding; Robert L. McCrory, present LLE CEO and Director; Donald K. Hess, University of Rochester Vice President at the time of the Laboratory's founding and, along with Sproull, key to its successful implementation; Jay M. Eastman, LLE Director 1981–1982 and project manager for the original OMEGA 24-beam Laser System.

Bottom (left to right): The ZETA target chamber used to conduct experiments with the first six beams of the 24-beam OMEGA system; the OMEGA EP laser (LLE's latest laser facility) activated in 2008; the 60-beam OMEGA target chamber area during a target shot taken in 2008; the 60-beam OMEGA laser amplifiers during a shot taken during the system activation in 1995; and the original 24-beam OMEGA laser activated in 1980. In the background is a photograph taken of a target shot inside the target chamber of the 60-beam OMEGA laser.

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Highlights of the History of the University of Rochester's Laboratory for Laser Energetics

Foreword

This year the University of Rochester's Laboratory for Laser Energetics (LLE) celebrates its 40th year. An anniversary provides the opportunity to reflect on the triumphs and difficulties of the past and to be reinvigorated by future challenges and goals that must be set and achieved. LLE accomplishments, marked by the innovation and brilliance that have received international attention for 40 years, have been possible because of the dedication, talent, creativity, and resolve of the research team—the scientists, faculty, students, and staff of the Laboratory. Equally important in our history are the support and funding LLE has received from our major sponsors including the University, private industry, the State of New York, and the Federal government. The collective accomplishments of the Laboratory are testimony to the tradition of scientific and technical excellence that marks the rich history of the University of Rochester.

LLE is a unique national resource for research and education in science and technology and a major asset of the University. The Rochester area and the University have a history of innovation that provides a singular environment for LLE within a technologically sophisticated scientific community, resulting in substantial regional economic impact. Established in 1970 as a center for the investigation of the interaction of intense radiation with matter, LLE has a five-fold mission: (1) to conduct laser-fusion implosion experiments in support of the National Inertial Confinement Fusion (ICF) program; (2) to develop new laser and materials technologies; (3) to provide education in electro-optics, high-power lasers, high-energy-density physics, plasma physics, and nuclear fusion technology; (4) to conduct research and development in advanced technology related to high-energy-density physics; and (5) to operate the National Laser Users' Facility (NLUF).

The year 2010 marks the 50th anniversary of the invention of the laser. The year is also the 81st anniversary of The Institute of Optics, one of the exceptional departments within the Hajim School of Engineering and Applied Sciences. The potential of the laser was immediately recognized at the University because of the excellence and expertise of both the University of Rochester faculty and the Rochester community in the physical sciences, particularly physics and optics. Exceptional leadership at the University, especially that of the University's 7th President, Robert L. Sproull, a well-respected physicist and administrator as well as a former director of the U.S. Government's Advanced Research Projects Agency, led to the establishment of the Laboratory in 1970. This document, prepared in large part by Dr. John Soures, whose professional career spans LLE's entire history, provides a brief history of the Laboratory for Laser Energetics as we prepare for what is most likely the most exciting time in history in the quest and grand challenge to tame nuclear fusion for the good of mankind.

Thermonuclear fusion is the process by which low-atomic-weight nuclei such as hydrogen combine to form a higher-atomic-weight nucleus such as helium. Two isotopes of hydrogen—deuterium (composed of a hydrogen nucleus containing one neutron and one proton) and tritium (a hydrogen nucleus containing one proton and two neutrons)—provide the most energetically favorable fusion reactants. In the fusion process some of the mass of the original nuclei is transformed to energy in the form of high-energy particles. Energy from fusion reactions is the most basic form of energy in the universe; our sun and all other stars produce energy by thermonuclear fusion reactions. The most significant long-term potential commercial application of fusion is the generation of electric power. Fusion does not generate nuclear waste nor does it enhance nuclear proliferation concerns, in contrast to the nuclear fission reactors currently in use. The fuel for fusion, which occurs naturally in water, is essentially inexhaustible. A demonstration of "ignition," the beginning of a self-sustaining fusion reaction, in the laboratory is expected in the next few years on the National Ignition Facility (NIF), a $3.5 billion facility built by the U.S. Department of Energy's National Nuclear Security Administration at Lawrence Livermore National Laboratory. LLE is one of the four institutional partners in the NIF and, as part of this National effort, is justifiably proud to stand on the threshold of the realization of fusion energy with our national research partners.

The OMEGA Laser System and the OMEGA EP Laser System are the pre-eminent facilities within the inertial fusion and high-energy-density physics communities that support an important national mission. Extensive use of OMEGA is essential to the national program to achieve ignition, to provide laser facility time for national laboratory experiments, and to operate the NLUF. OMEGA is the staging and support facility for the NIF. External users currently account for approximately 50% of the use of OMEGA. LLE's principal collaborating institution in inertial fusion research is Lawrence Livermore National Laboratory (LLNL). Additionally, the Laboratory benefits from strong strategic alliances with the Massachusetts Institute of Technology (MIT) and the State University of New York (SUNY) at Geneseo to further its educational mission and increase the number of technically qualified people in the field.

The long-term viability of the Laboratory has been due in part to a strategy that contains options that have been responsive to changing national research priorities and the complex political realities associated with any large national effort. High-energy-density physics is a new field that has been created based on advances in extending the power, energy, and intensity of lasers that make it possible to create matter under extremely high pressure (from more than a million to billions of atmospheres) in the laboratory. The field is rich in physical phenomena and compelling applications that will challenge the best minds and require state-of-the-art facilities for many years. The Laboratory takes great pride in the intellectual freedom that has provided our scientists the flexibility to exploit and develop paths that have opened new scientific horizons for the world. As one example, Professor Gerard Mourou and his Ultrafast Science Group were the first to demonstrate chirped-pulse–amplification (CPA) techniques for lasers, which opened the field of ultrahigh-intensity laser research. LLE advances in laser science and technology position the University of Rochester to be a leader in high-energy-density physics for many years.

Education is a core mission of both the University and the Laboratory. Since its founding, 191 students have received their Ph.D. degrees based on research carried out at the Laboratory. Currently, 85 graduate students are conducting research and 29 undergraduate students are working at the Laboratory. More than 100 Ph.D.'s have been granted at other institutions through the NLUF program. A research program for high school students that began in 1989 has produced 28 semifinalists and 4 finalists in the Intel Science Talent Search. Many of these students have gone on to obtain advanced degrees in the physical sciences or engineering.

LLE's activities include the development of technologies to support its research mission. As a relatively small facility, competing with the national laboratories, LLE has relied on its technology development to perform cutting-edge research and to maintain a competitive advantage. Technology development provides a fertile opportunity to develop sources of external funding, to stimulate collaboration with River Campus faculty, and to establish interactions with industry. A number of LLE-developed technologies have been commercialized, benefiting local and national companies.

On a personal note, the 40th anniversary of the Laboratory is a very special occasion. It is my great privilege and pleasure to have served as Director since 1983. I have been at LLE during the most intensely productive period of the Laboratory's history as we grew large enough to be effective and remained small enough to be agile. We are now in a position to see the promise of fusion realized. The Laboratory is one element that makes the University of Rochester a unique institution among its peers. The Laboratory is a feature of the University that is both prominent and important to the University's research base. Reflecting on the past 40 years and the excitement and potential richness of the future before us, I can only think of how much more can and will be done. It is my sincere wish that you enjoy reading this brief history of LLE.

Robert L. McCrory
Professor, Physics and Astronomy
Professor, Mechanical Engineering
CEO and Director, Laboratory for Laser Energetics
Vice Provost, University of Rochester

4 October 2010

Prelude

The invention and development of the laser in the 20th century were preceded by a burst of major scientific creativity that ushered in the era of "modern physics."

The first step was *Planck's Postulate* in 1900. Although Planck originally introduced this idea as a pure theoretical formality, the concept was used by Albert Einstein in 1905 to describe the photoelectric effect. Max Karl Ernst Ludwig Planck was awarded the Nobel Prize in Physics in 1918 "*in recognition of the services he rendered to the advancement of Physics by his discovery of energy quanta*," while Albert Einstein gained the Nobel Prize in 1921 "*for his services to Theoretical Physics, and especially for his discovery of the law of the photoelectric effect*."

The next step came in 1913 when Niels Bohr introduced the concept of the atom as a small positively charged nucleus surrounded by electrons that traverse in circles about the nucleus. Bohr was awarded the Nobel Prize in Physics in 1922 "*for his services in the investigation of the structure of atoms and of the radiation emanating from them*."

The final theoretical breakthrough leading up to the invention of the laser was Albert Einstein's realization in 1917 of the concept of stimulated emission. Einstein theorized that an excited atom could return to a lower energy state via the emission of a photon (he called this "spontaneous emission"). He likewise hypothesized that a photon traversing a material with excited atoms could stimulate such transitions and therefore generate "stimulated emission." This idea underlies the laser (i.e., light amplification by stimulated emission of radiation) and maser (microwave amplification by stimulated emission of radiation) concepts.

The first physical manifestation of Einstein's concept was the demonstration by Charles Townes in the United States in 1953–1954 of the maser. Meanwhile, in the Soviet Union, Nikolay Basov and Aleksandr Prokhorov independently developed the maser concept. The three scientists were joint winners of the 1964 Nobel Prize in Physics "*for fundamental work in the field of quantum electronics, which has led to the construction of oscillators and amplifiers based on the maser–laser principle*."

In the mid and late 1950s, Charles Townes and Arthur Schawlow at Bell Laboratories and Gordon Gould at Columbia University independently worked on concepts involving optical pumping of optical amplifiers. Gould used the term "laser" for the first time at a conference in Ann Arbor in 1959, and he filed an application for a patent on the laser concept in the same year. The U.S. Patent Department denied Gould's application and awarded the first laser patent to Bell Labs in 1960. This was the start of a nearly 30-year battle between the opposing forces, but patents were finally awarded to Gould in 1987 for the optically pumped and gas discharge lasers.

The first physical realization of optically pumped stimulated emission was demonstrated by Theodore Maiman of Hughes Research Laboratories on 16 May 1960 using flash-lamp–pumped ruby as the lasing medium [1].

The University of Rochester Laser Program:
The Early Years (1960–1975)

Within months of the announcement of Maiman's breakthrough, Michael Hercher at the University of Rochester's (UR) Institute of Optics (IO) initiated his doctoral research effort aimed at understanding the ruby laser. Hercher's doctoral dissertation was completed by 1964 but he continued his interests in high-power lasers as an IO faculty member and in 1965 his ruby-laser–induced air-spark demonstrations captured the imagination of a new faculty member in the University's Department of Mechanical and Aerospace Sciences (MAS)—Moshe J. Lubin.

Lubin was born in Tel Aviv, graduated from the Israel Institute of Technology in Haifa, and came to the United States to study aeronautical engineering at Cornell University (from which he received his Ph.D. in 1965).

Lubin was attracted to the solid-state laser because of its ability to generate high focused light intensities and therefore high energy density. His interests in pursuing the study of intense laser radiation with matter resonated well with a small group of faculty with plasma physics interests in the University's MAS Department and the prolific optics and laser expertise within the IO. Initial ruby and glass laser development and laser–matter interaction studies were undertaken. Exploratory funding came from the National Science Foundation, the Air Force Office of Scientific Research, New York State, and the University of Rochester. Donations of equipment (laser glass, power conditioning, etc.) from Eastman Kodak were important to the emerging facility. Faculty participation included Moshe J. Lubin (MAS–LLE Director), Michael Hercher (IO), H. Searl Dunn (MAS), James Forsyth (IO), and Albert Simon (MAS). Some of the programs that were carried out in this emerging laboratory included basic laser–matter interaction studies, laser development, interaction of magnetic fields with laser-produced plasmas, electrodynamic suspension of laser-fusion targets, short-pulse–laser development, and other studies of intense laser radiation interaction with matter.

By 1970, Lubin and his early colleagues at Rochester and elsewhere came to the conclusion that lasers could generate sufficiently high energy density in matter to ignite thermonuclear reactions. Lubin's team had the vision to prove the concept that through inertial fusion with lasers, one could light a small star in the laboratory and, thereby, potentially provide an alternative energy source.

Moshe J. Lubin (1938–1993) was the founding director of LLE.

Rochester, of course, was not alone in this realization. Preliminary efforts that eventually led to the world's largest inertial fusion program began at LLNL in 1962 using a ruby laser. John Nuckolls, a LLNL physicist who later became LLNL Laboratory Director, began calculations in 1960 to estimate the smallest energy that would be required to achieve ignition. He estimated at that time that as little as 1 mg of DT could be ignited and burned, yielding about 50 MJ of energy [2]. A major milestone moment for the ICF field was the 1972 Nature publication [3] by Nuckolls *et al*. predicting inertial fusion ignition with as little as 1 kJ of laser energy while high-gain implosions were predicted to require ~1 MJ of energy. Although we now know that ignition requires at least 100's of kJ of energy, the high-gain requirements are not significantly higher. The importance of the Nuckolls paper in 1972 was not so much the estimated required energy level for ignition, but the first open discussion of the concept of compression of targets to very high density to achieve efficient thermonuclear burn.

John Nuckolls provided much of the intellectual driving force behind the inertial fusion program at LLNL. His ideas influenced the path of inertial fusion development not only at LLNL but elsewhere including LLE. The LLNL and LLE ICF programs have traveled a parallel path since the early 1970s: LLNL has concentrated on the indirect-drive approach to ICF, while LLE has concentrated on direct-drive implosions. The researchers from both institutions have developed a high regard for each other's contributions to ICF and have found ways to amplify each other's efforts by utilizing to the maximum extent the breakthroughs developed by the other laboratory in their own unique situations.

John Emmett was a key figure in the history of the LLNL laser program. Emmett was working on disk-laser-amplifier development at the Naval Research Laboratory when he was invited to join LLNL in 1972 as the leader of a newly formed laser division. He served LLNL as Associate Director (AD) for Lasers from 1975 to 1989 and had a major role in the development of the LLNL laser development program including the Argus, Shiva, Novette, and Nova lasers. The LLNL laser program grew from 125 people in 1975 to 1700 during his tenure as AD. It was clear to LLE that LLNL could be a formidable competitor in the ICF field but could just as well play the role of a formidable ally and collaborator. LLE management chose the latter approach in its interactions with the LLNL program.

With the strong support of Robert Sproull, then President of the University, LLE was founded in the fall of 1970. The mission of the Laboratory was to investigate the interaction of intense laser radiation with matter. Principal funding for LLE came from the University of Rochester, the State of New York, and private corporations. The Laboratory was an interdisciplinary entity within the College of Engineering and Applied Science and the Director (Moshe Lubin) reported directly to the University President.

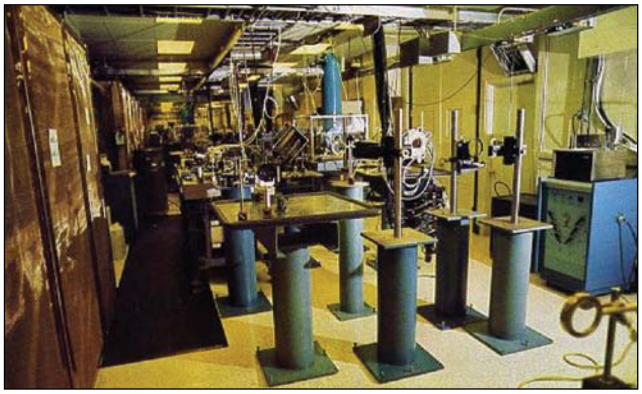
An early exposition on laser-fusion concepts appeared in "Fusion by Laser" published by Lubin and Frass in 1971 in Scientific American [4]. This paper discussed basic elements of a Nd:glass laser system, temporal tailoring of laser pulses, absorption of laser light, neutron production from laser-heated plasmas, break-even energy of ~0.1 to 1.0 MJ, and a conceptual laser-fusion reactor with thick liquid walls of lithium (the Blascon reactor).

By 1972, the Laser Fusion Feasibility Project (LFFP) came into being. LFFP was among the nation's first privately funded research efforts in laser fusion, and it represents to this day the largest single contribution to laser-fusion research outside the federal government. Exxon and General Electric were the first two major industrial sponsors of LFFP and were joined later by Northeast Utilities, New York State Energy Research and Development Authority, Empire State Electric Energy Research Corporation, Southern California Edison, Standard Oil of Ohio (SOHIO), and Ontario Hydro.

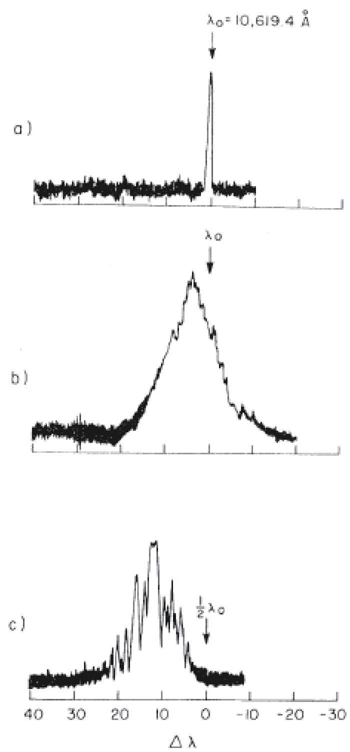
Between 1971 and 1975, the first four-beam LLE system, DELTA, was built and operated [5]. DELTA was an ~1-kJ Nd:glass laser used to investigate the interaction of high-power laser radiation and plasma with particular emphasis on laser fusion. During this period, Len Goldman, a physicist on loan from General Electric who later became a permanent staff member and University professor, John Soures, one of the first graduates of LLE who later became its first Experimental Division Director, and Moshe Lubin published the results of experiments showing the saturation of stimulated-Brillouin-scattered (SBS) radiation in laser plasmas [6] and other LLE investigations of short-pulse-laser–heated fusion plasmas [7].

The LLE team in the early 1970s. Lubin is seated in the center and flanked by John Soures (right) and Len Goldman (left). Immediately behind Len Goldman is Edward Goldman and next to him is Allan Hauer, at that time a graduate student and now Chief Scientist, Stockpile Stewardship, at the National Nuclear Security Administration, U.S. Department of Energy.

President Robert L. Sproull (right) and Vice President Donald Hess were key to the successful implementation of LLE in a precarious financial environment.

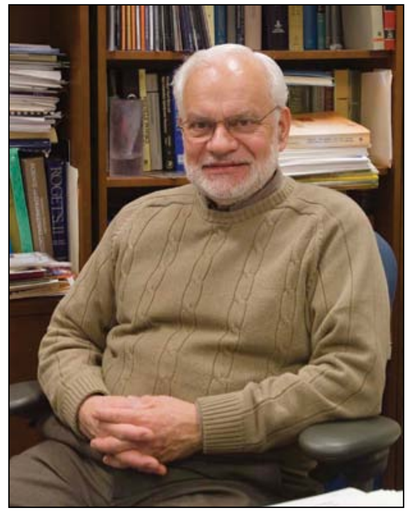


Photograph of the DELTA laser from the 1972 LFFP brochure.



Spectral measurements made on an early laser–matter interaction experiment [6], in which single 30-J, 120-ps-wide laser pulses were used to irradiate a 150-μm-diam LiD target: (a) incident laser light, (b) backscattered light near the fundamental frequency, and (c) backscattered light near the second-harmonic frequency.

Edward Goldman, who headed the LLE theory effort at that time, published results on numerical modeling [8–10]. At the time, there was also an interest in the use of laser fusion for the production of fissile materials by one of LLE's major sponsors (General Electric) [11].



John Soures, one of the first graduates of LLE (1970), led the laser development effort for the 24-beam OMEGA laser and was LLE's first Experimental Division Director (1983–1995). He now serves as Manager of the NLUF and coordinates all of the external user activity at the Omega Laser Facility.

The Special Laser-Fusion Advisory Panel–1974/1975

In 1974, the U.S. Atomic Energy Commission (AEC) convened the Special Laser-Fusion Advisory Panel under Lawrence R. Hafstad to review and report to the Commission on the following areas:

1. *Potential payoffs and technical status of laser-fusion efforts in government and non-government areas.*

2. *Recommend appropriate roles for the government and private sector in the national fusion program.*

3. *Recommend appropriate interaction between the public and private sectors.*

4. *Recommend R&D strategy and appropriate support, if any, by the AEC of private efforts.*

The panel included John Foster (then Vice President, TRW), Roy Gould (Cal Tech), Jack Rosengren (R&D Associates), and Richard Schriever [Division of Military Application-Energy Research and Development Administration (DMA-ERDA)]. Advisors to the panel included Everett Beckner (Sandia), Keith Boyer (Los Alamos), Solomon Buchsbaum (Bell Labs), Francis Chen (UCLA), Carl Hausmann (LLNL), Robert Sproull (UR), and Chauncy Starr [Electric Power Research Institute (EPRI)].

The panel's findings and recommendations were

1. *The laser approach to fusion power is a potential alternative to magnetic fusion confinement and deserves broad support.*

2. *Laser fusion is still in a research phase: consequently, the program should be broad and encourage contributions from all sectors.*

3. *To create a truly national program, federal support for laser fusion should include funding of "external" projects outside the national laboratories.*

4. *Private sector support not sponsored by the national laboratories should be encouraged by a small, competent staff at the Energy Research and Development Administration (ERDA), which will ensure the impartiality of the review process and proper program balance.*

5. *The major obstacles to the practical production of power by laser fusion should be identified at an early date by detailed studies of power systems.*

6. *Recent declassification action has effectively removed barriers to adequate exchange of laser-fusion research information.*

7. *ERDA should facilitate industrial and university participation by liberalizing its administration of patents, taking full advantage of flexibility in overall government patent policy.*

In its report, the panel confirmed that a practical power plant would require pellet gains in excess of 75 (assuming a laser efficiency of 10%). The panel also concluded that it would be difficult, but not impossible, to achieve ignition and high gain. It estimated that engineering breakeven would require lasers with energy greater than 1 MJ and practical power plant conditions might require close to 100-MJ output from the laser [12].

Energy Research and Development Administration (ERDA) Sponsorship

A key year in the history of LLE was 1975. It became readily apparent that the visions of Lubin's team—to build and operate a very large, 24-beam IR laser facility to be called OMEGA—would cost tens of millions of dollars. The invaluable annual research grants from the first sponsors—energy companies and the State of New York—amounted to tens of thousands of dollars during LLE's formative years. The underwriting of OMEGA, however, was significantly beyond their ability.

While President Sproull was totally supportive of proceeding with OMEGA, he made it abundantly clear that it had to be funded by sources from outside the University. This would be a Herculean burden requiring fulfillment in a very short span of time—approximately one year—to retain the amassed research staff. Lubin believed he could successfully shoulder the responsibility with some assistance. President Sproull was willing to help as his time permitted. Moreover, he permitted Donald Hess, who had recently joined the University as Vice President for Administration after 20 years of service in various federal government agencies, to assist in the endeavor. In effect, this team of three took on the funding challenge.

While the University had hoped the private sector and government agencies would commit to meeting the financial needs, with the federal government funding the laser, the State providing the building, and industry footing the annual operations, it quickly became clear that the existing and prospective new industry sponsors would not be willing partners to the unusual degree required. (Later in the decade, the Three Mile Island incident made matters worse for industry involvement.) This left the federal government as the last resort for underwriting the cost of the laser as well as research operations.

Up until 1975, nothing had been done in Washington in the way of seeking funds for the program. It was January 1975, and the President's budget had already been submitted to the Congress. Extraordinary time and work would be required to obtain funding for FY76. The Atomic Energy Commission (AEC) was the only realistic source of the needed funds, but it had just been disbanded and a new agency, the ERDA, would take its place. Fortunately, President Sproull knew the newly named administrator of ERDA, Dr. Robert Seamans, Jr., and was able to get an appointment with him the second day of ERDA's existence. While he could not make changes to the federal budget pending on Capitol Hill, he very much liked the Rochester program. He was especially intrigued by the University's desire to involve industrial and state sponsors. Most significantly, he gave the University authorization to present its case to the Congress so that LLE might be funded in ERDA's pending budget.

At this time, too, the Joint House–Senate Committee on Atomic Energy still existed. It, in effect, authorized and appropriated for ERDA. Rochester's congressman, Frank Horton, had just been appointed to the Committee. He arranged for the Committee to hear about the LLE program and the University's plea for funds from the ERDA budget.

Each of the major AEC contractors appeared annually before the Joint Committee to justify their programs and budgets. UR would ask that the ERDA budget be amended to provide for LLE. Donald Hess negotiated with the Committee staff for Rochester to be last to testify because Lubin was fearful that anyone who followed him would challenge Rochester's right to be funded from the ERDA appropriation for defense programs, the source of laser program funds.

It was agreed that the existing contractors, mainly the weapons laboratories, would testify ahead of Rochester. Lubin was pleased. But in calling the Committee to order for the hearing, the sequence of testifiers was changed: Lubin would be next to last and Dr. Keeve (Kip) Siegel, president of KMS Fusion, a contractor based in Michigan, would be last. Lubin was now most dispirited, but there was no choice!

Lubin testified. Then Dr. Siegel began his testimony. About two minutes into his presentation he had a stroke and died. The Committee immediately announced a conclusion of its FY76 laser-fusion budget hearing and adjourned the Committee.

It is impossible to know what would have happened had the original order of testifiers been maintained with Lubin following Siegel, as was desired. Likely the University would not have been able to present the LLE case and ask for funding. The Rochester program did get its requested funding. This was provided through a specific congressional line item provision to protect it because LLE funds were not made incremental to the ERDA budget. Rather they had to be absorbed in the existing weapons programs budget. Earmarking by Congress of the LLE program persisted throughout a number of years until the Department of Energy (DOE) initiated annual requests in its budget.

Director Robert L. McCrory joined LLE in 1976 and was its first Theoretical Division Director. He is now serving as Vice Provost, University of Rochester, CEO and Director–Laboratory for Laser Energetics, and is Professor of Physics and Astronomy and Professor of Mechanical Engineering.

Following the demise of the Joint Committee, Congressman Horton continued to provide invaluable support in the standard appropriations committee. Congressman Samuel Stratton (Rochester Class of 1937), chair of a House Armed Services subcommittee responsible for authorization, always provided strong oversight of the LLE program. Another critical time juncture occurred a few years later when DOE wished to combine the energy fusion programs, which would have meant moving LLE out of the weapons category for authorization and funding. While for some that made sense because the Rochester program was totally unclassified and it would remove LLE as a rogue competitor to the national weapons laboratories' approach to achieving fusion; for LLE it was a grave concern because the domestic fusion programs had great difficulty in acquiring the necessary sustaining funding level. Moreover, Sam Stratton's keen oversight on Rochester's behalf would have been lost. (Stratton personally wanted to retain the program because no committee chair enjoys erosion of a power base through the loss of an exciting and promising program.) Once again, through persistent follow-through in Washington, the LLE program position prevailed.

Robert L. McCrory and the Los Alamos Connection

The LLE ICF target design effort was significantly enhanced in 1976 with the arrival of Robert L. McCrory. A graduate of MIT (Applied Plasma Physics), McCrory became interested in ICF after hearing a talk by Keith Brueckner related to his work at KMS Fusion in Ann Arbor, Michigan. This inspired him to read Nuckolls *et al.* [3] and later Brueckner and Jorna [13]. After completing his Ph.D. thesis on the theory of drift and drift cone modes of a collisionless plasma in cylindrical geometry [14], he accepted a position in the Advanced Concepts Group led by Richard Morse in the Weapons Design Division at Los Alamos National Laboratory (LANL) in 1973.

The group at Los Alamos was studying laser fusion with emphasis on CO_2 lasers. At the time, a <1-kJ glass laser was under construction, but, as with all high-peak-power glass lasers at the time, the laser was performing considerably below the design specifications. Almost all of the LANL ICF work at the time was classified since the first major declassification in inertial confinement fusion did not occur until 1974. The only topic allowed in open discussions was laser fusion in a solid spherical target illuminated by a highly shaped laser pulse [3].

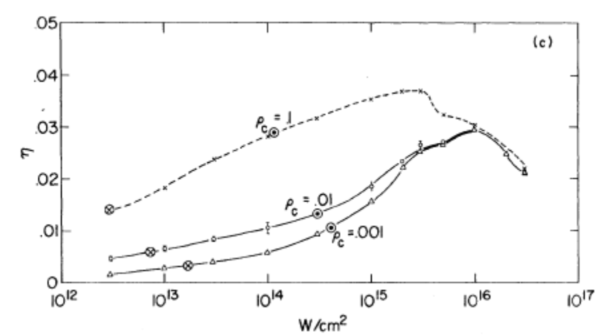
At Los Alamos, McCrory was introduced to a number of implosion codes that had been modified from their original form used in nuclear weapons design. Gary Fraley, Eldon Linnebur, Rodney Mason, and Richard Morse were using these "legacy codes" to study DT burn [15] and ICF dynamics. Richard Morse believed that a new code was needed that would be written with ICF in mind from the start. Morse had hired Robert Remund and Keith Taggart to develop two-dimensional particle-in-cell (PIC) hydrodynamics codes, and he tasked other group members to develop codes for other purposes. Under his direction, McCrory developed a one-dimensional hydrodynamic implosion code with a perturbation capability (*PANSY*). While McCrory was developing this code, Robert Malone joined the Los Alamos group after graduating from Cornell. Under Morse's direction, Malone developed another one-dimensional hydrodynamics implosion code (without perturbations) to simulate current experiments with the CO_2 laser. At the same time, other members of the Los Alamos theoretical group were using PIC methods to understand laser–plasma interactions. Don DuBois, Dave Forslund, Joe Kindel, Ken Lee, Erick Lindman, and Brendon Godfrey were all working on various aspects of laser–matter interaction physics. It was a lively group of scientists, and in the summer of 1974 Hans Bethe and Marshall Rosenbluth spent a number of weeks working with these two groups.

In 1974, McCrory co-authored his first paper on inertial confinement fusion, "Ablation Stability of Laser-Driven Implosions" [16]. To conform with the classification rules at the time of this publication, the example case in the paper was a solid DT sphere illuminated by a shaped pulse. A group at LLE published a paper with a similar approach in Physical Review Letters [17].

Richard Morse was very well organized and had divided his two groups into various working elements to support the Los Alamos effort in inertial fusion. McCrory was Robert Malone's officemate, and the two worked well together in developing these codes. The experimental results of Damon Giovanielli, Robert Godwin, and Gene McCall (in the experimental group at Los Alamos) with CO_2 raised a number of interesting questions. The bremsstrahlung spectra had higher intensities at photon energies near 50 keV than one would expect from classical electron thermal conduction. Also, the fraction of incident light transmitted by thin foils was less than expected, and the current of ions expanding from thick foils exhibited a two-humped distribution as a function of velocity. Robert Malone, Richard Morse, and McCrory proposed a flux-limited model of electron thermal conduction to model the experimental data [18]. The paper that Malone, McCrory, and Morse published in Physical Review Letters (PRL) in 1975 [19] became a "classic" in inertial fusion research. This article has been cited more than any other article co-authored by McCrory to date and has stimulated a great deal of theoretical work using Fokker–Planck codes and other methods to understand anomalous electron thermal transport in laser plasmas. Electron transport in laser plasmas is also an important and fundamental issue in modern research on fast ignition [20]. While McCrory has published on a great number of topics, this 1975 PRL paper is one of his most important contributions.

When classification guidance was changed, the Los Alamos group had a chance to publish some of their work on multi-shell and multilayered targets. This work first appeared as "Implosion, Stability, and Burn of Multi-Shell Fusion Pellets" [21]. At the same time, most researchers in inertial fusion research began to worry about mix and turbulence. McCrory and Morse wrote a paper on turbulent pusher behavior [22] using a phenomenological model similar to that of Belen'kii and Fradkin [23]. With other members of the group, they also published "Two Dimensional Studies of Turbulent Instabilities in High Aspect Ratio Laser Fusion Targets" [24].

Based on the LANL experience with CO_2, and on data from other facilities using glass lasers, Morse and McCrory began to doubt whether CO_2, despite the efficiency of the laser, would ever be suitable for laser fusion. In addition, experiments at Los Alamos were showing that the CO_2 laser energy was absorbed into highly energetic ("suprathermal") electrons that preheated the fuel and failed to contribute to an ablative implosion. The paper "Dependence of Laser-Driven Compression Efficiency on Wavelength" [25] concluded that the hydrodynamic efficiency of laser-driven implosions varied inversely with wavelength.



Plot from the McCrory and Morse paper of 1977 [25] showing the predicted dependence of hydrodynamic efficiency on the laser intensity for different values of critical density. The paper concluded that the hydrodynamic efficiency in laser-driven implosions would increase by a factor of 3 to 5 if the laser wavelength was reduced from the infrared to the ultraviolet.

This was the last paper that McCrory published while he was at Los Alamos. Richard Morse had decided to leave Los Alamos, and the two groups were reorganized. McCrory become very impressed by the very small but highly spirited effort of the group led by Moshe Lubin at LLE. In the summer of 1976 he joined the LLE scientific staff to lead the LLE target design effort.

GDL, ZETA, and OMEGA

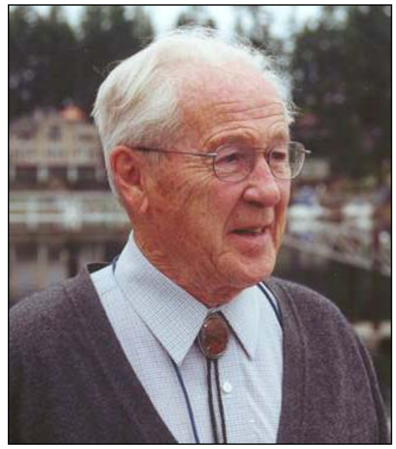
The cornerstone-laying ceremony for the new LLE building to house the new laser facility took place on 2 April 1976. The new building, based on architectural design work by United Engineers and including the engineering design efforts of Eastman Kodak, included 100,000 square feet of laboratory and office space. The part of the building housing the laser was specially designed for clean operations in a well-controlled temperature and humidity environment and was decoupled from the rest of the building's foundations to minimize vibration coupling to the laser equipment.

During the period from 1975 to 1980, the Glass Development Laser (GDL, 1-beam), ZETA (6-beam), and OMEGA (24-beam) laser systems were constructed and began operations [26,27]. GDL was a prototype beamline for OMEGA and demonstrated its 0.75-TW/beam performance in 1977. ZETA was a proof-of-design system incorporating the first six beams of OMEGA. It included a separate target chamber and operated for the first time in 1978.

The dedication of the new laboratory took place on 17 October 1978 with OMEGA in its ZETA configuration. It was a memorable day for everyone involved with the LLE program. Some 200 scientists, politicians, industry representatives, and government officials attended the event, which included the first-ever public firing of a laser onto a DT-filled glass shell. The Laboratory held its collective breath as the Honorable Frank Horton pushed the computer keyboard button that commanded the system to fire on target. To everyone's delight (and surprise), not only did the laser system perform flawlessly, but the target shot even produced in excess of 300 million neutrons. For the LLE staff, who had been working around the clock for weeks to bring the laser system up to the point where it could operate as a laser, let alone fire on a real target, this was a very special event and the harbinger of many future successes to come.

An important contributing factor toward the success of the LLE laser projects has been the close collaboration and contact with the Rochester-area optics community. For example, a key contributor to the optics design effort on OMEGA was Robert E. Hopkins—a former Director of the UR IO and the founder of Tropel, Inc. Optical coating technology and special optics fabrication continue to be areas of excellence for the University. The IO initiated the Thin-Film Coatings Laboratory and Optical Fabrication Shop. Both of these resources contributed greatly to the LLE laser development and construction efforts, and their management was eventually transferred to LLE.

LLE also profited greatly from the infusion of highly capable engineering talent from Eastman Kodak. Kodak engineers



One of the key contributors to the OMEGA laser was Robert E. Hopkins (1915–2009) who served as the "Chief Optical Engineer" for the project. "Hoppy," as he was known to his colleagues and friends, had a long and distinguished career at the University of Rochester as Professor of Optics and Director of The Institute of Optics (1954–1964). His lens designs included the Todd-AO lens used to film "Oklahoma." In 1967 he left the University to serve as President of Tropel, Inc.—a company he co-founded, which is now a division of Corning, Inc.—but he continued to teach at the University.

Stephen Jacobs was key in the development of the phosphate laser glass for the OMEGA laser [28–30], the development of liquid crystal optical components for OMEGA and frequency-conversion crystals, and the development and commercialization of magnetorheological finishing (MRF). He currently leads the optical materials effort at LLE.

Jay Eastman served as the Project Manager for the 24-beam OMEGA laser and as the second LLE Director. He is now Chief Executive Officer of Lucid, Inc., a Rochester-based company he founded in 1991 that provides specialized noninvasive skin-imaging technologies.

The GDL one-beam prototype laser operated for laser development and laser–matter interaction experiments at LLE from 1977 through 1993. Its major accomplishments include design validation of OMEGA; large-aperture amplifier development; the demonstration of high-efficiency frequency tripling; UV laser–matter interaction experiments; and the first NLUF experiments at LLE [26].

View of the 24-beam OMEGA laser.

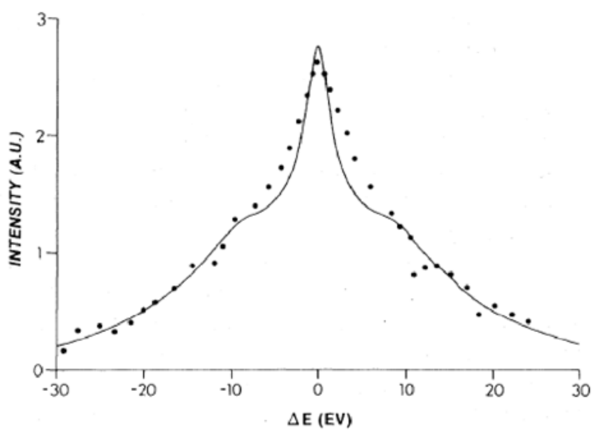
and managers were located on-site during the entire period of design, construction, and activation. The resulting GDL, ZETA, and OMEGA laser systems were at the forefront of ICF lasers in terms of cost effectiveness, reliability, and operational performance.

Experimental Program: 1975–1981

During the late 1970s, the Laboratory became clearly identified as the nexus of activity on the direct-drive approach to inertial fusion. The LLE experimental and theoretical programs were historically well integrated and synergistic. This situation was probably due to several factors, including the following: LLE was a small laboratory operating on a relatively small budget and it could ill afford to be burdened by the organizational overhead associated with its large competitors; the staff and its leaders were drawn from diverse scientific and technical backgrounds and many of them had both experimental and theoretical expertise. LLE has continued to place a premium on broad intellectual bandwidth for newly hired scientific and engineering staff.

The LLE experimental efforts during this period were directed at understanding the wavelength scaling of laser–matter coupling, developing diagnostic tools for the study of implosion physics, and validating the early hydrodynamic simulations being developed by the target designers.

Barukh Yaakobi and colleagues were among the first to experimentally use Stark-broadened x-ray lines to measure plasma densities [31]. This period also saw the first measurements of electron preheat [32] and hydrodynamic efficiency [33]. Among the other diagnostic techniques that were improved or developed during this period at LLE were high-speed streak cameras [34,35]; spatially resolved x-ray spectroscopy [36]; harmonic light emission [37]; charged-fusion-particle spectroscopy [38]; zone-plate coded imaging of charged fusion particles [39]; neutron knock-on measurements of fuel areal density [40]; and time-resolved x-ray diffraction [41].



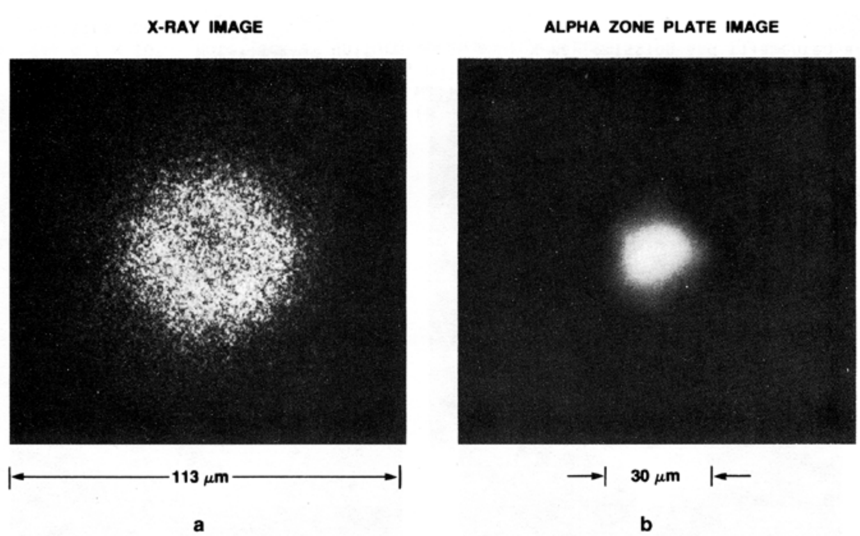
The first direct measurement of compressed density using the Stark-broadening of spectral lines. The experiment was conducted on the DELTA laser. Glass shells filled with neon gas were imploded with 40-ps, 0.2-TW pulses. The graph compares the calculated (solid curve) line profile of the Lyman-γ of neon, at an electron density of 7×10^{22} cm^{-3} to the measurements (dotted curve) [31].

In addition to previously mentioned research scientists and University teaching faculty, the participants in the experimental program during the late 1970s included Bill Friedman (another former Lubin student), Sam Letzring (at that time a graduate student), Barukh Yaakobi, Len Goldman, Gil Leppelmeier, James Forsyth, Abe Nee, Israel Pelah (visiting from Israel), Allan Hauer (graduate student), Steve Jackel (graduate student), David Woodall, Eric Thorsos, Tom Bristow, Bruce Perry, Joshua Gur (graduate student), Bob Turner (graduate student), Duncan Steel, Brian Nicholson, Joe Rizzo, Ed Lazarus, Alan Entenberg, Kazuo Tanaka (graduate student), Eugene Kowaluk, Frank Kalk (graduate student), and Robert Boni. Responsibility for leading the experimental group changed hands several times during the transition period from 1973 to 1979.

By 1979, the LLE divisional structure was established with Experimental, Theoretical, Engineering, and Administrative Divisions. John Soures and Robert McCrory were appointed as the first Experimental and Theoretical Division Directors, respectively; Jay Eastman became the Director of Engineering. The Laboratory is still organized along this divisional structure.

Theoretical Program: 1975–1981

The theoretical effort during the period 1975–1981 included Robert McCrory, Ed Goldman, Stan Skupsky, Jacques Delettrez, Steve Craxton, Jim Albritton, Charles Verdon, Peter Cato, Reuben Epstein, Mike True, Ed Williams, and Al Simon as well as contributions from visiting scientists such as Dov Shvarts from Ben Gurion University. Much of the effort of that time was dedicated toward baselining the LLE 1-D hydrocode *LILAC* [42]; improving the understanding of laser–plasma inter-



(a) X-ray pinhole camera image and (b) alpha zone plate image from an "exploding pusher"–type target shot taken on ZETA with a laser power of 1.8 TW (62-ps pulse width). The neutron yield from this DT-filled glass shell target was 1.1×10^9 [39].

actions [25,43]; developing the theory of long-mean-free-path electrons in laser-fusion plasmas [44]; developing the theory of hydrodynamic instabilities in implosions [45,46]; devising computational algorithms [47,48]; and creating theoretical models for frequency-conversion techniques in support of laser development [49].

Considerable time was spent modeling OMEGA exploding pusher experiments. A suprathermal electron package was developed for *LILAC*, which was essential for modeling the data [50]. An atomic physics/spectroscopic processor was developed to model the Stark-broadened lines used in the experiments to infer compressed density. During this period, LLE began the study of thermonuclear burn physics that would lead to its future ignition/high-gain target-design program and to the development and modeling of nuclear diagnostics [51,52].

Target Fabrication: 1975–1981

Target fabrication and development has been another important element of the LLE fusion experiments program. Since its inception, LLE has made and continues to make important contributions to this element of ICF research. As an example, one of the earliest experiments involving cryogenically cooled deuterium targets was carried out on the DELTA laser using a cryostat devised by Friedman *et al.* [53]. The initial target fabrication activities at LLE were part of the Exxon-contributed effort to the LFFP program and included Exxon staff members Gerald Halpern, Harry Deckman, Josh Varon, Irv Goldstein, and Dennis Peiffer working with LLE technical staff that included Jerry Drumheller, John Dunsmuir, Tom Powers, and Bernie Brinker. By 1981, the target fabrication effort was taken over by SOHIO under the direction of John Miller (originally of LANL). Other scientists and technologists who joined this effort included David Glocker, Hyo-gun Kim (who later led the LLE Target Fabrication Group), John Cavese, Luther Whitaker, Steve Noyes (who developed the spider-silk target suspension technology [54]), and John Reynolds.

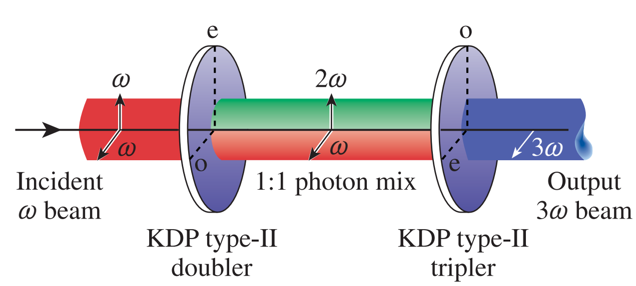
In spite of the relatively small size of the LLE target fabrication effort, it made important contributions to the early state of the art of this technology including the development of drill, fill, and plug techniques; coating of smooth polymer layers; radiographic characterization of targets; target suspension techniques; hemishell fabrication; and other important technologies [see, e.g., Ref. 55].

High-Efficiency Frequency Tripling

A separate "Brand X" laser effort (to identify a practical, high-efficiency, short-wavelength, high-repetition-rate laser for laser-fusion applications) continued for most of the late 1970s at LLE. This effort was carried out by Jack Wilson and Dave Ham and examined various candidate short-wavelength laser schemes [56,57]. Although some promising candidates were identified, no practical fusion laser ensued from this effort.

However, because the advantages of shorter-wavelength laser irradiation appeared to be very compelling [25] and experiments (particularly at the École Polytechnique under the leadership of Edouard Fabre) had shown improved absorption at short wavelengths, LLE explored other means of developing a short-wavelength irradiation laser. In an effective partnership of the theoretical, experimental, and engineering divisions in the period 1979 to 1980, the Polarization Mismatch scheme for frequency conversion was invented and patented by LLE and became a standard for fusion lasers all over the world [49,58,59]. This approach uses a KDP (potassium–dihydrogen–phosphate) crystal to convert two-thirds of the energy of a Nd:glass laser's output at a wavelength of 1.054 μm to its second harmonic at a wavelength of 0.527 μm. The remaining 1.054-μm light is mixed with the second-harmonic light in a second crystal to produce the third harmonic at 0.351 μm. By properly choosing the crystal orientations and laser polarization, it was demonstrated that 80% of the Nd:glass laser light could routinely be converted to its third harmonic using this technique. Since the UV light was ten times more effective than IR light in coupling into and driving an ICF capsule implosion, this invention was akin to boosting the energy of existing glass lasers by nearly an order of magnitude.

The team responsible for this important result included Stephen Craxton (lead theoretical physicist), Wolf Seka (lead experimental physicist), Joe Rizzo, Robert Boni, and Stephen Jacobs. It was Craxton's elegant concept of "polarization mismatch" that led to the breakthrough that solved this difficult puzzle. Craxton was the ideal person for this project. He made a hobby of solving impossible geometrical puzzles, approaching them with a sense of confidence and delight that trivialized them in short order.



Schematic illustration of Craxton's frequency-tripling scheme.

Stephen Craxton (left) and Wolf Seka (right) led the LLE effort to develop an efficient frequency-conversion scheme. The full 24-beam OMEGA laser was frequency converted to the ultraviolet in 1985 (bottom).

Departure of Founding Director

By 1981, SOHIO had become one of the main private sponsors of the Laboratory, ostensibly to help develop microfabrication technology that was considered important for such applications as solar cells. In return it provided LLE with some of the target fabrication support required to carry out ICF experiments. By this time, Moshe Lubin, LLE's founding director, found the challenge of a lead position in a major oil company irresistible and accepted an offer to take over as Vice President of Research for SOHIO, running their research laboratory in Warrensville, Ohio. Several LLE scientists also left the Laboratory at this time to take on positions with SOHIO. Undoubtedly, this was one of the most precarious points in the Laboratory's history. Lubin's departure coupled with potential funding shortfalls created a somber atmosphere at LLE. Concurrently, the Laboratory's scientific and technical prospects appeared very bright in light of the success of the frequency-conversion demonstration.

Frequency Conversion Applied

Jay Eastman, who was the chief engineer in charge of building the 24-beam system, became director until late 1982 when he left the Laboratory to start a company (Optel) specializing in bar code scanners. This is one of many successful examples of the transfer of LLE-developed technology to the private sector.

The early 1980s presented the LLE management with some exciting new opportunities as well as some formidable challenges. It was clear that using shorter wavelengths appeared the most favorable approach for laser fusion. It was also clear that in order to embark on such a project, some hard budget choices had to be made. It was also necessary to obtain the approval of DOE. The LLE management decided to initiate a major effort to validate the physics of direct-drive ICF on OMEGA with UV irradiation.

After a hard battle, approval for the conversion of the 24-beam OMEGA laser to the third harmonic was finally obtained from DOE. In return, DOE insisted on a phased implementation of the conversion over a period of three years.

In concert with the senior laboratory staff, the LLE directors devised a program that necessitated substantial staffing and program cuts in order to create sufficient funds to invest in the development of frequency-conversion technology and its application to the full 24-beam OMEGA system. Approximately 20% to 25% of the LLE staff at the time had to be cut. This was a very tough task since the LLE scientists were some of the best in their area of expertise. There were probably some outside the Laboratory who did not believe that LLE would recover from this crisis.

On 1 January 1983, at the conclusion of a national search, Robert McCrory was appointed Director of the Laboratory. He, in turn, appointed John Soures as Deputy Director (in addition to Experimental Division Director), and McCrory also continued to direct the Theoretical Division.

The first six beams of OMEGA were converted and started operating in the UV in the third quarter of FY83 (1 October 1982 until 30 September 1983). During 1983, OMEGA and GDL were also operated for LLE experiments as well as for those carried out by NLUF users. GDL provided 894 target shots and 422 laser development shots while OMEGA provided 384 target shots and 798 shots in support of laser development and UV conversion during FY83.

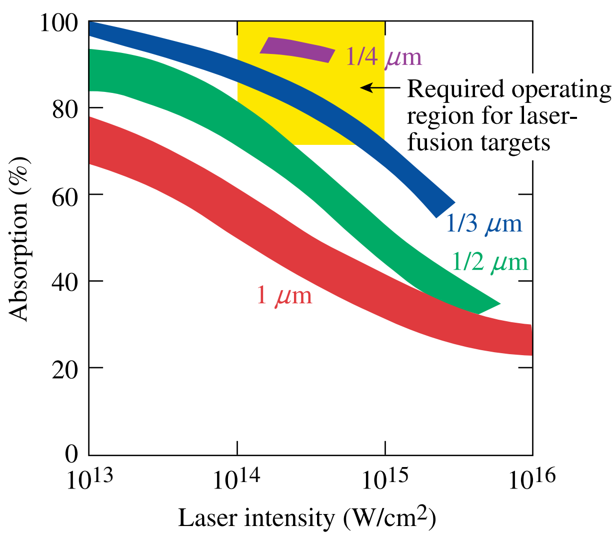
By the end of FY85, the full 24-beam UV conversion of OMEGA was completed—on time and on budget. McCrory struck a bargain with Robert Hutchison, the laser facility manager at that time, that if the UV conversion project was completed on time and within budget, the Laboratory would pay for a special dinner (at the restaurant of Hutchison's choice) for all the staff and their spouses (or significant others) involved in the project. McCrory decided on this approach because he

Beam splitting, amplification, and frequency tripling of the pre-1992 OMEGA 24-beam OMEGA laser were carried out in the large room shown here. The bright areas on the far wall are caused by flash lamps that energize the laser amplifiers. The laser beams are infrared, so they are invisible. They are converted into invisible ultraviolet light by crystals in the six box-like modules. The visible light emerging from some of the modules comes from heat lamps, switched on intermittently to keep the crystals at constant temperature. Residual green light from the conversion causes the green glow. The beams emerge from the modules in groups of four, and their energy is measured. Subsequently, the beams are reflected by the mirrors visible in the foreground into the adjacent target area [60].

knew that to successfully carry out this project would require significant sacrifices in time and effort by all the staff.

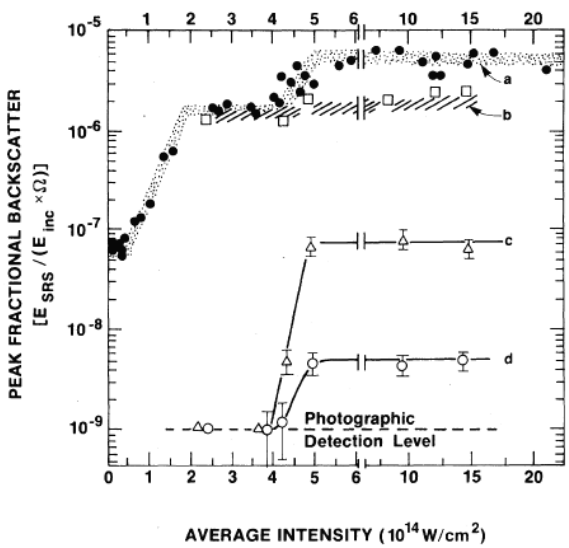
Upon the successful completion of the project on the specified terms, he asked Robert Hutchison for a list of people to attend the dinner. He was promptly handed a list of the entire LLE technical staff, explaining that all of these individuals had a hand in the UV conversion project. Hutchison also specified the Rio Bamba as the restaurant of choice—the most expensive restaurant in the city of Rochester at that time. McCrory approved this request. After the near-five-figure bill for the special dinner hit the University Accounting Department, the Director received a frantic call from one of the head accountants about the charge. McCrory referred the caller to the University's Vice President, Donald Hess, from whom he had already received permission for this extra special "compensation." Don not only approved the charge but also commented to the critic that other units of the University could well learn how to motivate their staff to extraordinary performance by this example.

During the period 1983–1987, significant work was carried out at LLE on characterizing the physics of UV laser–matter interaction [61–69]; developing tools for the design of high-performance, direct-drive ICF capsules; and developing high-density plasma diagnostics and direct-drive capsule fabrication and characterization capabilities. Some of the new additions to the experimental staff during this period included Ray Bahr, David Bradley, Paul Jaanimagi, Jim Knauer, Terry Kessler, Robert Keck, Robert Kremens, Frederick Marshall, Greg Pien,



Absorption experiments at different laser wavelengths show that the energy absorbed by the capsule increases as the laser wavelength decreases. The data are obtained from several experimental facilities including LLE, LLNL, and École Polytechnique.

and Martin Richardson. Since SOHIO phased out of the fusion program by the early 1980s, LLE also had to reconstitute the Target Fabrication Group. Hyo-gun Kim was appointed group leader and Roger Gram, Mark Wittman, and Cary Immesoete were added to this effort.



*Plot showing the intensity dependence of stimulated Raman scattering from early GDL laser experiments [63]. Curves **a** and **b** show the absolute backscattering measurements at 700 nm taken with absolutely calibrated photodiodes. Curve **a** represents scattered light polarized parallel to the incident laser; curve **b** represents the orthogonal polarization. Curves **c** and **d** are similar curves (but not absolutely calibrated) corresponding to the convective and absolute Raman instabilities, respectively.*

During this period McCrory continued to work with Richard Morse and his students on the ablation-driven Rayleigh–Taylor instability [70]. Charles Verdon was one of Richard Morse's students at the University of Arizona but moved to Rochester to complete his thesis with McCrory as his resident advisor. Charles wrote a two-dimensional Lagrangian hydrodynamics code with triangularly shaped zones (*DAISY*) as part of his thesis research. Because of difficulties with this zoning, Charles went on to write *ORCHID*, a two-dimensional hydrodynamics code with quadrilateral zones similar to the Livermore *LASNEX* [71] code. *ORCHID* has been used in the LLE design effort for many years. Other additions to the theoretical team during this period included Robert Short (Plasma Physics Group) and Patrick McKenty (Theory and Computation Group). In addition to Al Simon, University faculty collaborating with the Theoretical Division during this period included Larry Helfer and Hugh Van Horn.

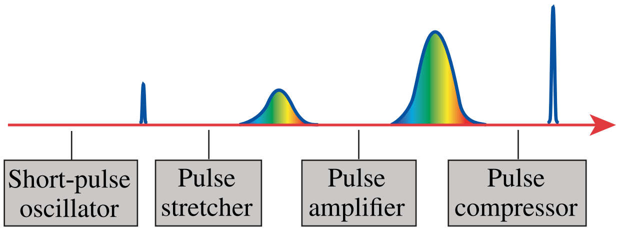
In August 1986, Stephen Craxton, John Soures, and Robert McCrory published "Progress in Laser Fusion" in Scientific American [60]. This article presented a summary of the 1986 state of the art of LLE's effort to validate the direct-drive approach to inertial fusion.

Ultrafast Science and Technology

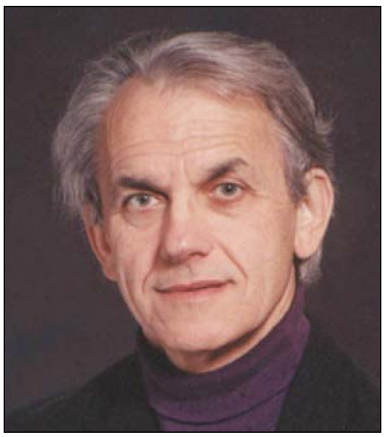
In spite of the pressures of financing the OMEGA effort in laser-fusion research, and following the recommendations of several University of Rochester Board of Trustees review committees, LLE made significant investments in ultrafast science and technology in the early 1980s. The rationalization for supporting this effort was based on several factors including the following: (a) to probe the extremes in energy and power density, (b) to provide advances in technology that might be important to the laser-fusion program, (c) to promote greater collaboration with the University of Rochester academic departments and colleges, and (d) to provide directions for growth for the Laboratory research program.

The Ultrafast Sciences Group was headed by Gerard Mourou (who joined the Laboratory around 1979) and included several LLE staff, graduate students, and University faculty. Some of the faculty involved in the effort included Robert Knox, Tom Hsiang, Conger Gabel, Mark Sceats, Roman Sobolewski, Joe Eberly, and Adrian Melissinos. Among the LLE staff brought into this program were William Donaldson, Phillipe Bado, Maurice Pessot, Hani Elsayed-Ali, and Steve Williamson. A large number of graduate students (especially from IO and Electrical Engineering) were attracted to this research and made important contributions to the program, including Wayne Knox, John Nees, Tod Norris, Alan Krisiloff, James Kafka, John Whittaker, Charles Bamber, Larry Kingsley, Tom Juhasz, Doug Dykaar, Donna Strickland, Steven Augst, John Squier, Don Harter, Janis Valdmanis, Tod Sizer II, Irl Duling III, and Kevin Meyer.

This dynamic group was prolific and contributed many firsts to LLE's long list of innovations including high-power switching with picosecond precision [72]; picosecond microwave pulse generation [73]; picosecond electron diffraction [74]; picosecond and subpicosecond electrical sampling [75]; and femtosecond pulse generation [76,77]. Of particular note was the development of the chirped-pulse–amplification (CPA) technique that made it possible to generate ultrashort laser pulses using conventional Nd:glass lasers [78]. This technique was the enabling technology for the development of petawatt lasers that are now of exceptional interest in the investigation of high-energy-density science. Gerard Mourou eventually left the UR in 1988 to start his own laboratory (The Ultrafast Science Center) at the University of Michigan. He is now the Project Coordinator of the Extreme



Chirped-pulse amplification (CPA) was developed at LLE in 1985 and used to produce very high intensity ultrashort laser pulses.



Gerard Mourou headed Ultrafast Science at LLE from 1979 to 1988. He and his group produced many important innovations including ultrafast electro-optic sampling, high-power picosecond switching, and chirped-pulse amplification (CPA). Gerard is currently Project Coordinator for the Extreme Light Infrastructure (ELI) project in France.

As a graduate student at The Institute of Optics, Donna Strickland did her Ph.D. research in the LLE Ultrafast Group and co-developed the CPA technique that is the basis of all petawatt laser systems. Donna is now a professor of physics at the University of Waterloo in Canada.

Light Infrastructure (ELI) project, a European program to probe ultrahigh-intensity laser–matter interaction.

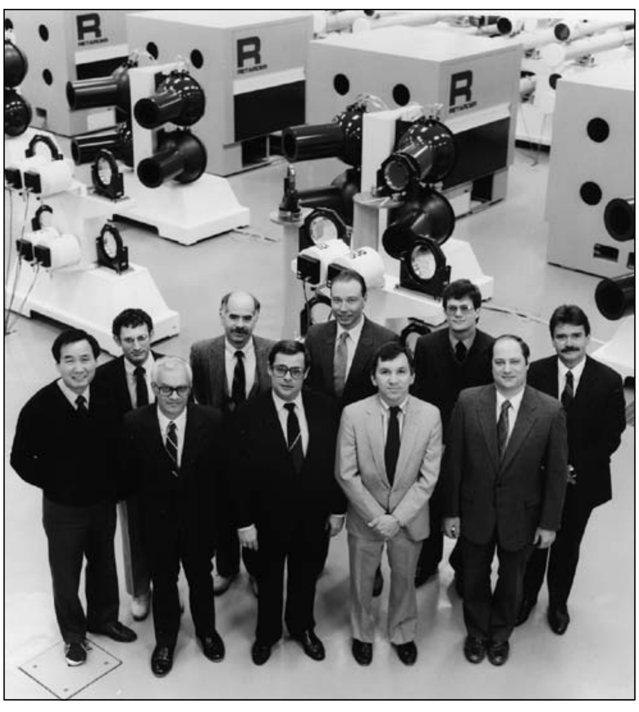
High-Density Compression—The Challenge

By the mid-1980s, while LLE was reaping the scientific benefits of the UV-converted OMEGA and looking to the future validation of direct drive, DOE was looking to put the overall ICF program on solid ground. The National Research Council of the National Academy of Sciences (NAS) was asked to conduct a review of the program in the mid-1980s. The NAS Committee (chaired by W. Happer) concluded its review of the Department of Energy's ICF Program in March 1986. This review was conducted in response to a request from the White House Office of Science and Technology Policy. The review recognized the important work being done by LLE in addressing the key aspects of ICF research and set a goal of compressing a cryogenic direct-drive target to a density of 100 to 200 times liquid DT density as a demonstration that would justify the upgrade of the OMEGA laser to 30 kJ [79].

The Laboratory's efforts were effectively channeled to meeting this important experimental objective. A KMS Fusion cryogenic target system was installed on OMEGA and modified by LLE to meet the specifications of OMEGA experiments [80]. To meet the direct-drive uniformity objectives, distributed phase plates (DPP's) were developed and constructed by LLE [81].

The cryogenic system for these experiments used the "fast refreeze" technique originally developed at KMS Fusion. This system allowed LLE to form thin layers (typically ~10 μm thick) inside relatively small (~380-μm-diam), DT-filled (75- to 100-atm) glass shells. The targets were supported by spider silk drawn across a U-shaped copper mount. The assembly was coated with a 0.2-μm-thick parylene coating to give it mechanical stability. The initial plan was for KMS to develop a prototype system using a simulation chamber, which would be used to train LLE personnel on the operation of the cryogenic target system and would then be followed by a full-up system on the OMEGA chamber. The simulation system (which was based on the old ZETA chamber) arrived at LLE in September 1986. A training session ensued after which it was decided to proceed directly to OMEGA implementation, using as much of the ZETA simulation chamber hardware as possible. Interface hardware arrived from KMS in 1987, and by mid-June the complete cryogenic target system had been installed on the OMEGA chamber. Several laser shots were taken during the summer and early fall before it was decided to suspend shots in order to carry out several system redesigns. Among the principal problems faced at that time were target vibration, unpredictable cryogenic shroud retraction, and poor DT-layer quality.

The principal parts of the cryogenic system were (1) a liquid-He–cooled target-positioning stage; (2) a liquid-helium–cooled shroud and shroud retractor system; (3) the reheating system (a laser that was flashed on briefly to vaporize the frozen DT fuel); and (4) the target documentation (characterization) system. The original shroud retraction system designed by KMS used a vacuum bellows and electromagnetic release to provide the motive force for retracting the cooling shroud. This system proved to be very unreliable because the timing of the system was dependent upon the residual magnetism in the release electromagnet and was therefore prone to failure by early release. Sam Letzring (Group Leader of the Diagnostics Development Group within the Experimental Division) was responsible for the redesign of the cryogenic system. The most-extensive redesign of the original system was in the retractor and mount. It was decided to replace the KMS retractor with a linear motor capable of producing 500 lb of pulling force and an acceleration of 10.6 g. Controlled deceleration was also specified to minimize the impulse delivered to the mounting structure. The motor was procured from Anorad Corp. of Hauppauge, NY, in little more than a month. In slightly more than seven weeks after the decision to redesign, the new motor was installed and tested. It met or exceeded all specifications. The lessons learned on this first OMEGA cryogenic system were important to the design of the much more challenging cryogenic system that was developed a decade later for current LLE experiments.

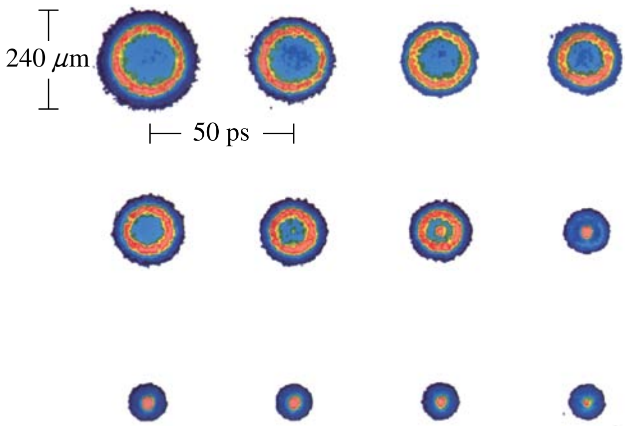


The team responsible for achieving the first LLE high-density cryogenic target milestone in 1988. Left to right: Hyo-gun Kim, Stephen Jacobs, John Soures, Stanley Skupsky, Robert McCrory, Frederick Marshall, Samuel Letzring, Terrance Kessler, James Knauer, and Robert Hutchison.

In parallel with the cryogenic system implementation, another team at LLE was developing systems to achieve the beam irradiation uniformity required to achieve ablative, low-entropy implosion of fuel capsules. Considerable theoretical effort was applied to determining the levels of uniformity that would be required [82]. In the period leading up to the cryogenic capsule experiments, LLE developed and implemented two-level distributed phase plates (DPP's) to control the irradiation pattern of the laser beams on target. Terry Kessler (Group Leader of the Optical Engineering Group within the Engineering Division at that time) led the development of the DPP's in collaboration with Doug Smith and his colleagues who ran the LLE-managed Thin Film Coating Facility. Larry Iwan, Eugene Kowaluk, Ying Lin, Charles Kellogg, Joseph Barone, and William Castle have worked with Kessler on various aspects of DPP development since that time.

The DPP's were composed of an ordered array of transparent hexagonal elements in which phase retardation was randomly distributed among the elements using a thin-film layer to introduce an optical-path-length difference of 1/2 of a wavelength (λ). Computerized image generation was used to produce a mask, and the mask was transferred to a fused-silica substrate using precision photolithographic techniques. A thin layer of SiO_2 was vapor deposited onto the resist-coated substrates and removed in a lift-off procedure to produce the phase plate. The fabrication procedure was accurate to $\lambda/50$ and was characterized to $\lambda/400$. Collimated laser light passing through the DPP was broken into 15,000 coherent phase-retarded beamlets and brought to focus on the target surface, where a superposition of all the beamlets took place. The resulting beam pattern was circular, very symmetric, and accentuated by high-frequency speckle attributed to the coherence of the laser. The use of the DPP's on OMEGA improved the overall uniformity by a factor of 6.

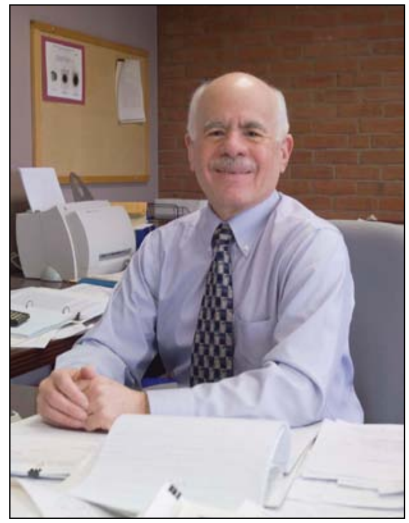
With the adapted cryogenic system and the newly developed beam smoothing, LLE demonstrated the goal of 100 to 200 times liquid DT density implosions on OMEGA as reported in Nature in 1988 [83,84]. An extensive array of experimental diagnostics was employed to carry out these experiments, including absorption and fractional conversion of the absorbed energy into x rays; time- and space-resolved measurements of x-ray emission; neutron yield and energy spectrum; and fuel-areal-density measurements using the "knock-on" diagnostic [40]. The knock-on diagnostic, in particular, gave unequivocal evidence of high density. It was the only diagnostic that could measure density in a temperature-independent way. This technique was conceived and developed at LLE. (The theoretical concept was first conceived, then the detection technique was developed—i.e., CR-39 track detectors, which are still being used—and finally the technique was implemented on the experiment.)



A high-speed framing camera developed at LLNL was used to image capsule implosions on the 24-beam OMEGA laser. The implosion-velocity data obtained from such experiments were used to analyze the results of the initial cryogenic capsule implosions in 1988. The first image at the upper left was taken some time after the beginning of the 700-ps-long, 1.5-kJ UV laser pulse used to implode a 240-μm-diam, 5-μm-thick glass shell filled with 25 atm of deuterium.

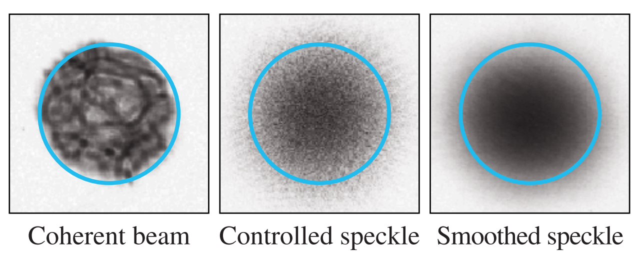
The experimental results were validated by an independent DOE panel in March 1988. This was the highest compressed fuel density recorded in ICF experiments (using either the direct- or indirect-drive approach) at that time and made a strong case for the direct-drive approach.

The subsequent invention and implementation on OMEGA of "smoothing by spectral dispersion (SSD)" significantly strengthened the case for the direct-drive approach [85]. The team that came up with this innovation included Stan Skupsky, Robert Short, Terry Kessler, Steve Craxton, Sam Letzring, and John Soures. The integrated LLE approach of combining theoretical and experimental scientists with engineers once again paid off. Just as the frequency-conversion breakthrough of 1980, SSD in 1989 became a universal solution to the uniformity issue of a glass laser system and was subsequently adopted on all major glass laser fusion facilities, including the NIF.

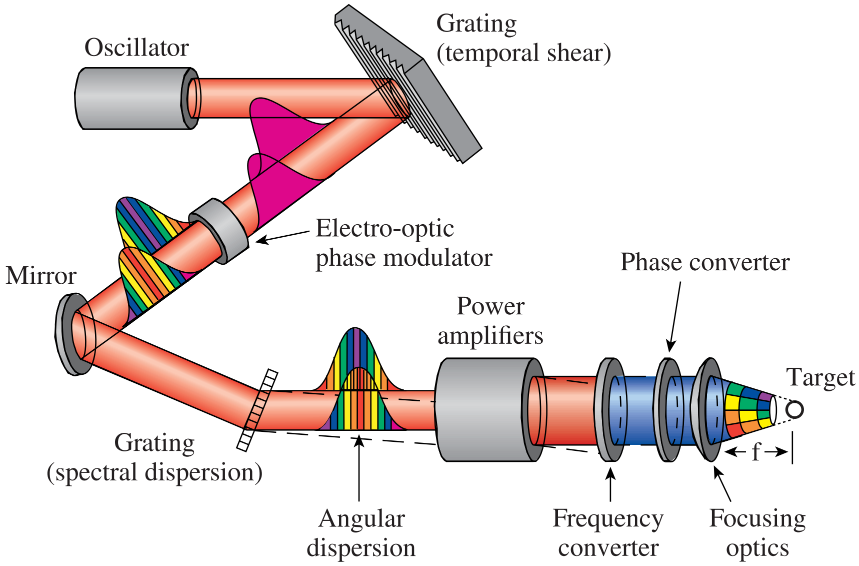


Stanley Skupsky made major contributions to beam smoothing for direct-drive ICF targets and serves as the LLE Theory Division Director.

LLE was motivated to pursue techniques to rapidly move the speckle pattern in the focal plane of the laser to achieve additional smoothing. The Naval Research Laboratory (NRL) had invented a novel smoothing technique (induced spatial incoherence) that had achieved considerable success in 1.06-μm-light experiments [86]. The NRL program manager, Steve Bodner, had stated that smoothing techniques with frequency-tripled light were not likely to be achieved because of the precise phase-matching requirements of the tripling process. The LLE team rose to this challenge. In recognition of the roles played by their respective teams in the innovation of laser-beam–smoothing techniques for ICF, the American Physical Society awarded the 1993 Award for Excellence in Plasma Physics Research to Y. Kato and K. Mima (Osaka University), R. H. Lehmberg and S. P. Obenschain (NRL), and S. Skupsky and J. M. Soures (UR/LLE).



The effect of beam smoothing is shown in these photographs of actual OMEGA beams taken at a position equivalent to that of a typical OMEGA target: left—unprocessed OMEGA UV beam at the target plane; center—on-target distribution using only distributed phase plates; and right—the smoothed distribution produced when SSD beam smoothing is applied.



Schematic illustrating the SSD concept.

Reviews of the ICF Program: 1988–1990

In the period 1988 to 1990, several reviews of the ICF Program were conducted that greatly influenced the direction of the program. An in-depth DOE review of target physics issues for direct- and indirect-drive targets held in November 1988 [87] concluded that the requirements and critical issues for the two approaches were quite similar and that direct drive should be pursued as a complement as well as an alternative to the indirect-drive approach. A key conclusion of the review was that both of these programs should address the physics issues that could reduce the minimum size of the proposed laboratory microfusion facility without additional risk.

By congressional mandate, a new NAS review of the program was undertaken in 1989. The review was chaired by Prof. S. Koonin of the California Institute of Technology and was initiated in June 1989 [88]. The Committee commented that there was a reasonable chance for a laboratory ignition and gain demonstration within the decade, given favorable results from a few crucial, well-defined experiments. Further, the Committee observed that the glass laser was the only viable laser driver candidate that could be used for an ignition demonstration within the proposed time. To implement this recommendation, the Committee made four more sub-recommendations: (1) provision for Precision Nova at LLNL; (2) funding to validate the laser architecture proposed for the Nova Upgrade at LLNL; (3) construction of the OMEGA Upgrade at LLE; and (4) focusing of DOE management of ICF in a strong headquarters office and DOE establishment of an Inertial Confinement Fusion Advisory Committee. Specifically, the Committee's sub-recommendation was "We recommend that the proposed OMEGA Upgrade be started immediately. It will contribute to the technology and physics expertise needed for an ignition demonstration through the Nova Upgrade. It will be able to explore the option that the Nova Upgrade be configured for direct drive" [89]. The report also noted: "The LLE Program has been very productive, inventive, and cost effective; it is also an important university connection to ICF efforts in other countries" [89].

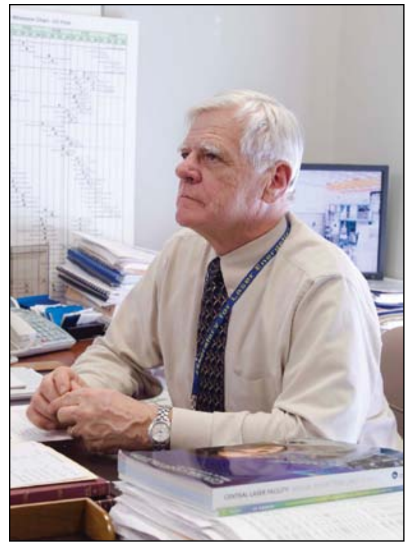
Another major review undertaken at this time was the Fusion Policy Advisory Committee (FPAC) review. The FPAC panel was formed by the Secretary of Energy to take a broad look at DOE's fusion program. The Secretary emphasized that his primary interest was to have the Committee provide its best judgment on the optimal way to structure the overall fusion program. FPAC was chaired by H. G. Stever and held its first meeting in March 1990; it submitted its final report in September 1990 [90]. The detailed FPAC report endorsed both the magnetic and inertial approaches to fusion energy. The Committee recommended a policy focused on a demonstration power plant to operate by 2025 and a commercial power plant by 2040. FPAC endorsed the construction of a Nova Upgrade (pending completion of the Precision Nova milestones). To provide further data to evaluate direct drive, FPAC endorsed the construction of the OMEGA Upgrade. The FPAC report emphasized the participation of universities in fusion science and technology and noted "With the exception of the University of Rochester, universities have played a minor role in inertial fusion…"

During FY90, DOE also carried out two independent reviews of the LLE inertial fusion program. The first of these was a technical review of the OMEGA Upgrade Preliminary Design (Title 1) on 7–8 November 1989 [91]. This review resulted in the approval of the conceptual design of the OMEGA Upgrade. The second review was conducted by the management and administration office (MA-22) of DOE and cost-validated the project. In the subsequent year, the detailed design of the system commenced, long-lead items were procured, and technology demonstration was continued to develop the power amplifiers for the Upgrade.

In 1993, the state of the ICF program was summarized in a Physics Today article that McCrory co-authored with John Lindl and Mike Campbell of LLNL [92].

LLE People

As the Laboratory collectively focused its attention to the OMEGA Upgrade, the management also embarked on an effort to strengthen LLE's scientific and engineering staff base. Important new additions to the staff were made in the late 1980s and 1990s. Captain Steven J. Loucks (USN, Ret.), a former nuclear submarine commander, was brought onboard as the Administrative Division Director in 1990. By 1994, Steve assumed the direction of the Engineering Division as well, with specific responsibility to conclude the OMEGA Upgrade project on time, within specifications, and on budget. Members added to the Engineering Division during the period ~1988–1997 included Lance Lund (a returning LLE veteran), Steve Kumpan (returning LLE veteran), David Lonobile (another returning LLE veteran), Milt Shoup, Robert Peck, Samuel F. B. Morse (related to the inventor of the Morse code and the grandson of a famous Princeton mathematician), Thomas Hinterman, Amy Rigatti, Doug Smith, Kurt Kubath, Frederick Rister, Mark Romanofsky, Judy Mathers, Joyce Truscott, Richard Fellows, Oscar Lopez-Raffo, Mark Russell, Wade Bittle, Harold Kramer, Keith Ebbecke, Giuseppe Raffaele-Addamo (a veteran LLE staff member), Phillip Torti, Norman Webb, Jason Hobler, Byra Ferkovich, William Christiano, Larry Folnsbee, Anthony Alongi, Gregory Brent, Terleta Willis, Christopher Cotton, Mark Guardalben, Todd Blalock, Paul Mittermeyer, Louis Santiago, Richard Whiteman (another LLE veteran), Keith Thorp, Ray Huff, Per Adamson, Michael Bacci, Cynthia Bahr, Matthew Kamm, Richard Kidder, David Kuhn, Scott Sandruck, Eric Schwartz, Alex Maltsev, Mikhail Kaplun, William Kinnear, Steven Brown, Roman Chrzan, Hope D'Alessandro, Richard Roides, Pat Dean, Glen Kowski, Sal LaDelia, Nelson LeBarron, Gary Mitchell, Art Staley, Bill Byrne, and Joy Warner. Some of the scientists who contributed to laser and optics development during the period of the late 1980s to the mid-1990s include Jack Kelly*, Stephen Jacobs*, Ansgar Schmid, Kenneth Marshall, Semyon Papernov, Shaw-Horng Chen (joint appointment with the Department of Chemical Engineering), and John Lambropoulos (joint appointment with the Department of Mechanical Engineering).



Captain Steven J. Loucks (USN, Ret.) led the effort to complete the OMEGA Upgrade project and organized a highly effective operating regimen for the Laser Facility. Loucks served as Administrative Division Director and Engineering Division Director and is currently the Principal Deputy for the National Ignition Campaign.

The Experimental Division staff was also increased during this period. Among the additions were David Meyerhofer (also a faculty member of the Department of Mechanical Engineering), David Harding (Target Fabrication Group Leader), Vladimir Glebov, Thomas Boehly*, Robert Kremens, Sean Regan, Andrey Okishev, Mark Skeldon, Jonathan Zuegel*, Mark Bonino, Brian Hughes, Mark Wittman, Karl Lintz, Sal Scarantino, Sara Bodensteiner, and Dave Turner. By 1996, John Soures stepped down from the Experimental Division Director and Deputy Director positions he had held for 17 and 13 years, respectively, and took on the management of the NLUF Program and the coordination of all external user activity on OMEGA; Wolf Seka assumed the position of Experimental Division Director and Charles Verdon assumed the Deputy Director position.

The Theory Division underwent major changes and additions during this period. Charles Verdon was appointed Division Director for Theory and a Software Development Group was added. Some of the new staff additions included Riccardo Betti (joint appointment with the Department of Mechanical Engineering), Radha Bahukutumbi, Eric Blackman, Adam Frank (joint appointment with the Physics Department), Evgeni Fedutenko, Richard Town, Alexander

*Former UR graduate student.

Ryskin, Anthony Brancato, John Mlyniec, Eric Natel, Ron Prine, Jeremy Wyatt, Mary Lee Farrow, Robert Rombaut, Dave Keller, Donna Lynch, and Diana Coppenbarger.

In the later years (1997 to the present) the Laboratory's staff continued to be strengthened to meet the ever-increasing scientific, engineering, and administrative challenges. David Meyerhofer succeeded Wolf Seka as Experimental Division Director in 2001, Stan Skupsky assumed the position of Theoretical Division Director in 1998, Steven Loucks assumed the Deputy Director position, and Craig Sangster joined LLE and was appointed Group Leader for the OMEGA Experimental Group. Other additions during this period included Vladimir Smalyuk*, Valeri Goncharov*, Suxing Hu, Jake Bromage, Christian Stoeckl, Leon Waxer*, Dustin Froula, Timothy Collins, John Marozas, Dana Edgell, Wolfgang Theobald, Walter Shmayda, Jason Myatt, Genady Fiksel, Igor Igumenshchev, Philip Nilson, Andrey Solodov, Christophe Dorrer, Andrei Maximov, Ildar Begishev, Samuel Roberts, Chuck Sorce, Noel Alfonso*, Bob Earley, Luke Elasky, Roger Janezic, Dale Guy, James Sailer, Kevin McGowan, Brian Harrod, Andrew Dillenbeck, Chris Fullone, George Gerspacher, John Reid, Thomas Storie, John Marciante, Hu Huang, Rhonda Cole, Mark Donovan, Timothy Flannery, Greg Brent, Steve Stagnitto, Mark Labuzetta, Matthew Arelline, James Barnash, Jeff Fisher, Jack Armstrong, Matthew Goheen, Jeff DeWandel, Stephanie Dent, James Eichinger, Joleen Knox, Matthew Maslyn, Benjamin Ruth, Ron Snyder, James Tellinghuisen, Jason Puth, David Weiner, David Scott, Brian Rice, Craig Robillard, Ajay Suthar, Howard Ammenheuser, Michael Bacci, Jackson DeBolt, Richard Dean, Stephen Foote, Brian Kruschwitz, Raymond Huff, Brian Lee, Eric Schwartz, Joann Starowitz, Tanya Kosc*, Andrew Baynes, Larry Carter, Sarah Curet, Mark Bedzyk, Tom Buczek, Glenn Gates, Franklin Ehrne, Jason Magoon, Adam Pruyne, David Canning, Jeffrey Ulreich, Charles Abbott, Thomas Lewis, John Szczepanksi, Ronald Callari, Steven Lombardo, Allen Cross, Gregory Kick, Victor Kobilanski, Larry Powell, Marcia Barry, Bruce Thaxton, Donald Farris, Dale Green, David Hassett, Michael Hofer, Ray Hopf, Scott Ingraham, Steven Reber, Troy Walker, Jeremy Coon, Scott Householder, Thi Nguyen, Scott Reed, Joseph Romano, Karen Monroe, Jalil Shojaie, Alexei Kozlov, Laurie Martin, Mark Bowman, Brian Charles, Vernon Gruschow, Vincent Guiliano, Jeffrey Hettrick, Steven Huber, Scott Hylas, Peter Kupinski, Salvatore LaDelia, Benjamin Laquitara, James Oliver, Dan Sadowski, Christopher Smith, Katie Leyrer, John Spaulding, Bruce Brannon, Timothy Duffy, Timothy Wilson, Mark Wilson, Emil Cost, Jie Qiao, Thomas Klingenberger, Richard Brown, Josee LaBar, William Noonan, Lawrence O'Heron, Oleksandr Shvydky, Michael Charissis, Kenneth Anderson*, Ralph Russo, Matthew Millechia, Steven Smith, Todd Touris, Michelle Burke, Miguel Cruz, Lhiling Tzuu, Chad Mileham, Seung-Whan Bahk, Kirk Cottom, Harold Beck, Cindy Dorfner, Brett Kingery, Alan Shechter, Matthew Callahan, Joshua Church, Timothy Davlin, Chad Fella, Kurt Herold, Sheryl Lucas, Dino Mastrosimone, Corey McAfee, Daniel Neyland, Jeffery Rodas, Michael Rowland, Mason Schleigh, Andrew Sorce, Robert Staerker, Daniele Walker, Michael Miller, Michael Arelline, Gregory Balonek, Albert Consentino, Elizabeth Hill, Scott Inscho, Lyndsey Kamm, James Kolacki, Matthew Moore, Marie Estelle LaBoy, Carol Meyers, Michael Spilatro, Alan Szydlowski, Douglas Szymanski, Sharyl Abbey, Brian Ehrich, Kyle Gibney, Jeffrey Hart, David Irwin, Adam Kalb, Geoffrey King, Colin Kingsley, Joseph Kwiatkowski, Brian Lee, Nermina Mahmutovic, Charles McMahon, Michael Ngo, Thahn Nguyen, Jennifer O'Sullivan, Michael Sacchitella, Patrick Shanley, Todd O. Smith, Todd A. Smith, Eric Bredesen, Dean Bredesen, Sean Carey, Bruce Glucksman, Stanley Holmes, Michael Scipione, Michael Koch, Patrick Regan, Steven Verbridge, Vera Versteeg, Alfred Weaver, Tammy Ammenheuser, and Robert Junquist.

In addition to those mentioned elsewhere in this historical accounting, the present members of the Administration Division, which provides all the essential support services for

David D. Meyerhofer is Deputy Director, Experimental Division Director, and Associate Director for Science at the Laboratory for Laser Energetics of the University of Rochester. He is also a Professor in the Departments of Mechanical Engineering and Physics & Astronomy, and a co-principal investigator of the University of Rochester Fusion Science Center. As division director, Dr. Meyerhofer leads a team of scientists, engineers, and technicians that focuses on designing and performing experiments on OMEGA along with developing and fabricating targets, diagnostics, and optical and laser technologies.

*Former LLE graduate student.

John Schoen joined LLE in 2001 as the Associate Director and Engineering Manager of the Center for Optics Manufacturing. In July 2005 he was appointed the Director of LLE's Administrative Division. Before joining the Laboratory, Schoen's career included 22 years at Eastman Kodak Company in the Optics and Equipment Divisions with assignments in development, product engineering, project management, and operations management. He also worked for Optical Coating Laboratory, Inc. as the engineering and product manager for its Rochester, NY, precision polymer optics facility.

the Laboratory, include Sharon Shinners, Barbara Cronkite, David Van Wey, Matt Weibel, William Byrne, Kathie Freson, Jacqueline Bryant, Robert Dash, Joseph Delisle, Kevin Flannery, Timothy Morris, Nicholas Pascucci, John Powell, Dan Raiber, Jasper Robinson, John Sawyer, Tyler Streeter, Michael Hussar, Jody Mayer, Paul Mittermeyer, Rhonda Solomon, Joseph Totten, Heidi Barcomb, Kara Carnahan, Jennifer Hamson, Karen Kiselycznyk, Lisa Stanzel, Jennifer Taylor, Trista Horning, Priscilla Betteridge, Barbara Bostic, Sarah Frasier, Barbara Sullivan, and Ellen Trafficante.

OMEGA Upgrade

The OMEGA Upgrade laser was designed to be a 60-beam UV laser with an energy-on-target capability of 30 kJ and an eventual irradiation uniformity of 1% to 2% rms. To maximize its experimental utility, the system was designed to shoot at least one shot per hour. The total system cost of the laser was budgeted at ~\$61M (i.e., ~\$2000 per UV joule). LLE surprised many people at DOE and the national laboratories by achieving the unachievable with respect to the new laser. Not only was the laser completed on time, its performance exceeded the specifications and its cost was within budget. As a point of comparison, note that the \$2000—in 1994 dollars—per UV joule cost of the OMEGA Upgrade is significantly lower than that of Nova (~\$4400 per UV joule in 1983 dollars) and comparable to the much larger NIF.

The preliminary design of the upgraded OMEGA system was completed in October 1989, and detailed design for the 4.5-year construction project commenced in October 1990. In December 1992, the 24-beam OMEGA laser fired its last shot before being decommissioned to allow for the construction of the upgraded laser. Ten months later, the building modifications were completed and laser construction began. In January 1994, the pulse-generation room (PGR) began operations, and in April 1994, the entire driver was activated. The first full OMEGA beamline was completed in December 1994 and produced 800 J in the IR and 606 J in the UV. On 1 February 1995, a single UV beam irradiated a target. In March 1995, the first full 60-beam laser shot was fired, and, in April 1995, all 60 beams irradiated a target. The final acceptance tests of the system were performed on 2 May 1995.

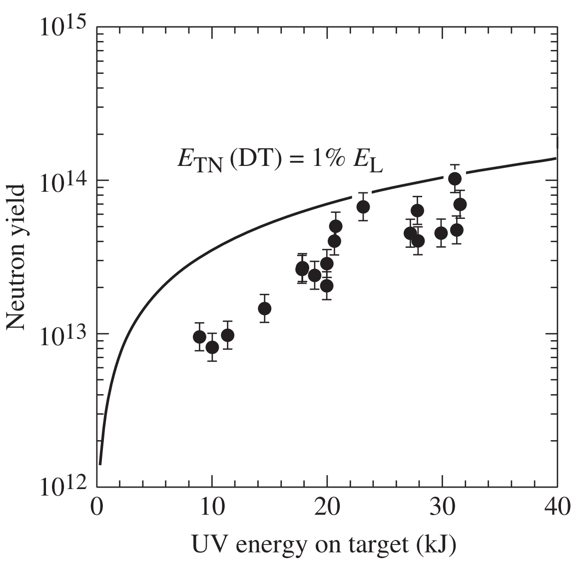
The acceptance criteria for the upgraded system were the demonstration of target irradiation with 30 kJ of UV energy in 60 beams, with ~750-ps Gaussian pulses, and the achievement of a beam-to-beam energy balance of 10% rms. For the acceptance tests, targets were irradiated with UV energies up to 37 kJ, and the beam-to-beam energy balance was better than 8%. Overall frequency-conversion efficiencies of 75% were routinely obtained. The full laser system operated for 15 shots with a 1-h shot cycle, including nine consecutive target shots. The system thus met or exceeded all acceptance criteria.

From its first shots in 1995, the OMEGA Upgrade has set the standard for ICF research for the subsequent 15 years. In its first experimental campaign with DT-fueled targets, the OMEGA Upgrade produced fusion neutron yields in excess of 1.3×10^{14}—or approximately 1% of the laser energy placed on target—exceeding by several times the yield obtained on the slightly higher energy Nova facility at LLNL [93]. This record fusion neutron yield stood for 15 years and was just recently surpassed in late 2010 in experiments being conducted at the NIF. It is appropriate that the experiments that exceeded the OMEGA neutron record of 1995 are being led by LLE scientists using diagnostics developed and implemented by LLE. The Laboratory is also providing the DT fills for the targets that were used on these early NIF implosions.

The purpose of the OMEGA Upgrade laser was to execute an experimental program to validate the direct-drive approach to fusion. Because of its high efficiency, direct drive may result in the achievement of ignition and high gain on the NIF.

The LLE experimental campaigns conducted on OMEGA to validate the direct-drive approach have resulted in noth-

Patrick McKenty (Group Leader of the Computational Design Group) led the theoretical effort for the 1995 laser-fusion target experiments that achieved a record nuclear fusion yield. He is currently involved in the design of polar-drive experiments for the NIF.

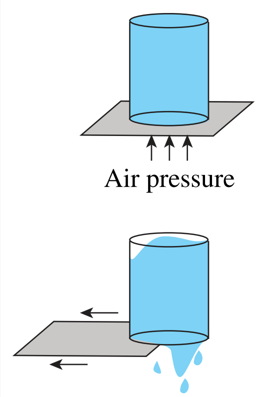


The highest neutron yield obtained in a laser-driven inertial fusion experiment as of September 2010 was attained on 60-beam OMEGA UV implosions in 1995 [from Ref. 93].

ing short of spectacular successes. These include integrated spherical experimental campaigns (designed to investigate the physics of direct-drive capsule implosions); long-scale-length plasma interaction physics campaigns (designed to investigate the interaction of intense laser radiation with large plasmas similar in parameters to those expected on the NIF); diagnostics development campaigns (designed to develop the diagnostics required to explore the core conditions of near-ignition capsules); Rayleigh–Taylor instability (RTI) campaigns (designed to investigate in detail the hydrodynamic instabilities of high-performance capsules); cryogenic capsule campaigns (designed to demonstrate cryogenic capsule performance scaling to ignition on the NIF); and experiments conducted in direct support of the DOE Stockpile Stewardship Program (these experiments are generally carried out in collaboration with scientists from the national laboratories).

In recognition of the "*Outstanding theoretical work, computational analysis, and experimental work leading to a quantitative and predictive understanding of the RT instability (RTI) in high-energy density physics*," the American Physical Society awarded the 1995 Award for Excellence in Plasma Physics Research to S. G. Glendinning, S. W. Haan, J. D. Kilkenny, D. Munro, B. A. Remington, S. V. Weber, and R. J. Wallace (all of LLNL), and to C. P. Verdon (LLE's Theory Division Director at that time and now serving as AX Division Leader at LLNL) and J. P. Knauer (of UR/LLE). The important contributions made to this work by the leadership of Joe Kilkenny are noted, first at the Rutherford Appleton Laboratory in the U.K. and later at LLNL.

The RTI occurs any time a dense fluid is suspended above a lower-density fluid. A good example is a glass full of water that is covered with a piece of paper and inverted. The water stays in place—suspended by the lower-density air—as long as the piece of paper is in place. When the paper is removed, the water spills out because of the effects of RTI. Small ripples in the interface between the air and the water grow in size and eventually cause the water to spill out of the glass. In a similar manner, in a laser-fusion target, the lower-density ablator



James Knauer was a co-recipient of the 1995 APS Award for Excellence in Plasma Physics Research for his experimental work on Rayleigh–Taylor instability (RTI). One of the many natural manifestations of RTI is illustrated by the inverted glass demonstration.

plasma pushes on the high-density plasma under compression. If there are variations in the pressure across the surface of the target, RTI can cause these variations to grow, and eventually the target is disrupted and falls apart.

The OMEGA Laser in the Mid-1990s

During the period 1995–1998, the OMEGA 60-beam UV laser became fully operational with pulse-shaping capability and broad-bandwidth, 2-D SSD [94]. Beginning in FY96, OMEGA began to provide shots for indirect-drive and other high-energy-density physics experiments from the national laboratories [LLNL, LANL, and Sandia National Laboratories (SNL)]. Two weeks of experiments were performed in June 1996 to demonstrate the utility of OMEGA for indirect drive. This campaign involved researchers from LANL, LLNL, and LLE. The main objective of these experiments was to validate the ability of the OMEGA system to perform hohlraum experiments, to reproduce results obtained with the Nova laser, and to demonstrate new capabilities not available on other lasers. All of these objectives were met.

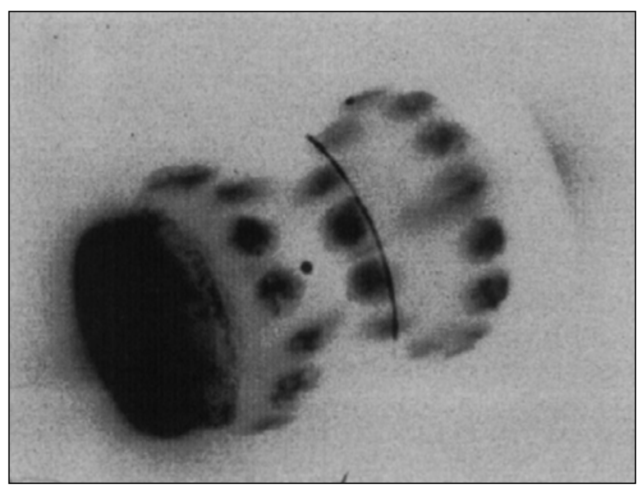
These experiments took advantage of key capabilities added to the upgraded OMEGA immediately after completion of the project including a new pulse-shaping system and a ten-inch diagnostic manipulator (TIM). The experiments were the first on OMEGA to simultaneously use three framing cameras. Most of these experiments were carried out using 1-ns square pulses, with 500 J per beam delivered to the target.

The OMEGA beams were configured in three beam cones on each side of cylindrical "scale-one," Nova-type, thin-walled hohlraums. The main purpose of the first series of experiments was to verify the ability of the system to point the beams to the appropriate locations. On the next series, a symmetry scan was conducted to verify the same dependence of hohlraum symmetry on beam pointing as was obtained with the previous Nova experiments.

The system's flexibility was amply demonstrated by carrying out high-quality, hohlraum-driven capsule implosions with 40 of its beams configured to irradiate cylindrical hohlraums with a three-ring beam pattern. The OMEGA hohlraum experiments are, in this way, closer to simulating the irradiation conditions of the NIF than was the old ten-beam Nova configuration [95,96].

To accommodate the increased demand for shots, the OMEGA operations time was extended. OMEGA's irradiation geometry also allowed novel hohlraum geometries, such

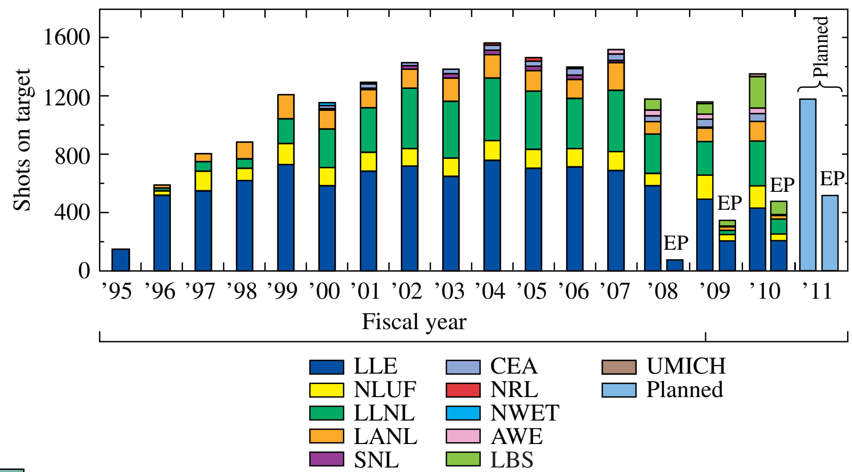
Target area (top) and laser bay (bottom) of the OMEGA 60-beam UV Laser System.



X-ray pinhole camera image of a thin-walled hohlraum implosion target [from Ref. 96] from one of the early hohlraum-drive experiments on OMEGA. The core of the imploded capsule at the center of the hohlraum is clearly seen, in addition to the joint in the hohlraum midplane made when mounting the capsule; the beam spots; and one laser-entrance hole on the left.

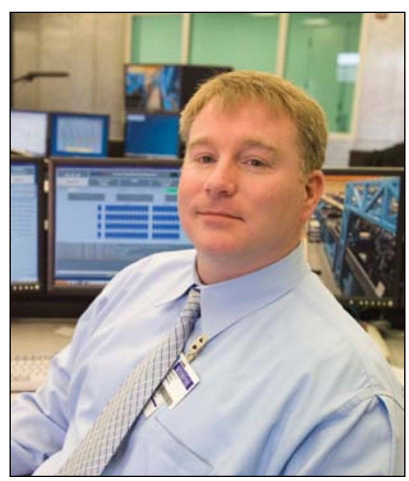
as "tetrahedral" hohlraums [97,98], to be explored. The target designs implemented for this later series of experiments were the outgrowth of design calculations carried out by Jeremy Schnittman (a student who originally came to LLE through the high-school research program sponsored each summer by LLE). Schnittman worked on these designs under the guidance of his mentor Steve Craxton.

The shot productivity of OMEGA since its upgrade in 1995 has been exceptional. Approximately 1500 target shots are taken each year, and approximately half are taken by external users (national laboratories, NLUF, etc.). Since 1995, 19,400 target shots have been taken at the Omega Laser Facility (including OMEGA EP). It is particularly important to note the efforts of Capt. Loucks and the Engineering Division managers and group leaders (especially Sam Morse, Keith Thorp, and Greg Pien) to develop and implement the organization and operational and training procedures that have led to a high level of productivity, system availability, and experimental effectiveness.



Graph illustrating the operations history of the OMEGA laser since its upgrade in 1995.

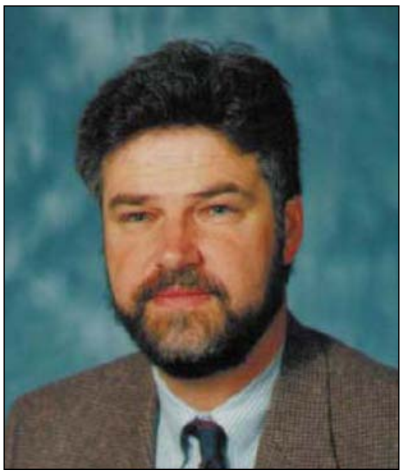
Samuel Morse is now the Director of the Omega Laser Facility. He is responsible for the operation of the OMEGA 60-beam laser, the OMEGA Extended Performance (EP) 4-beam laser, and the Cryogenic and Tritium Facility. He has worked on laser oscillators, aided in the frequency conversion of OMEGA from infrared to ultraviolet, and then managed the Laser Operations Group. From 1990–1995 he managed a large segment of the OMEGA Upgrade Project, rebuilding the OMEGA laser into a 60-beam facility. For the remainder of the 1990s, Sam was the Laser Facility Manager in charge of operational readiness and facility operation. In 2002 Sam was appointed Project Manager for OMEGA EP, responsible for construction of the OMEGA EP laser.



Keith Thorp is the Omega Laser Facility Manager with management responsibility for OMEGA and OMEGA EP.

The National Ignition Facility and National Laboratory Collaborations

The completion of the OMEGA construction coincided with the start of design for the National Ignition Facility (NIF). The NIF started construction in 1997 and is planned to achieve its goal of fusion ignition in the next few years. Compared to OMEGA, NIF is a gargantuan facility: it occupies a foot print nearly the size of the Superdome. NIF is capable of producing up to 1.8 MJ of UV energy; it consists of 192 laser beams of dimension 40 cm × 40 cm arranged into 48 quads. E. Michael Campbell, a physicist who led the experimental program on the Nova facility, led the effort to initiate NIF construction as the LLNL Associate Director of Laser Programs.



E. Michael Campbell led the Nova experiments effort at LLNL from 1986–1990. In the 1990s as Associate Director of Laser Programs, he led the effort to start the NIF. He later served as Executive Vice President at General Atomics and is currently Director, Energy Systems at Logos Technologies.

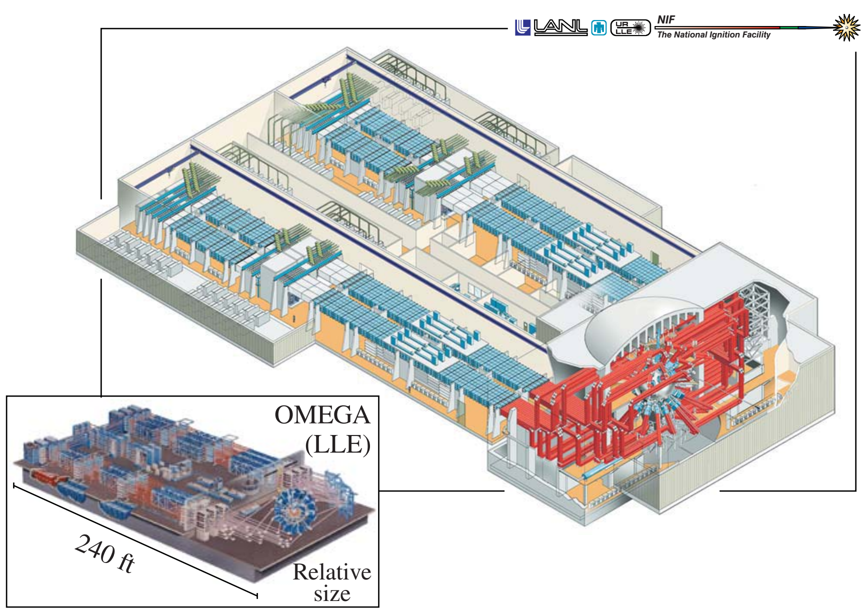
The validation of the capability of OMEGA to conduct indirect-drive experiments in 1996 ushered in an era of strong partnerships with the national laboratories (LLNL, LANL, and SNL) to conduct inertial fusion and high-energy-density physics experiments on OMEGA.

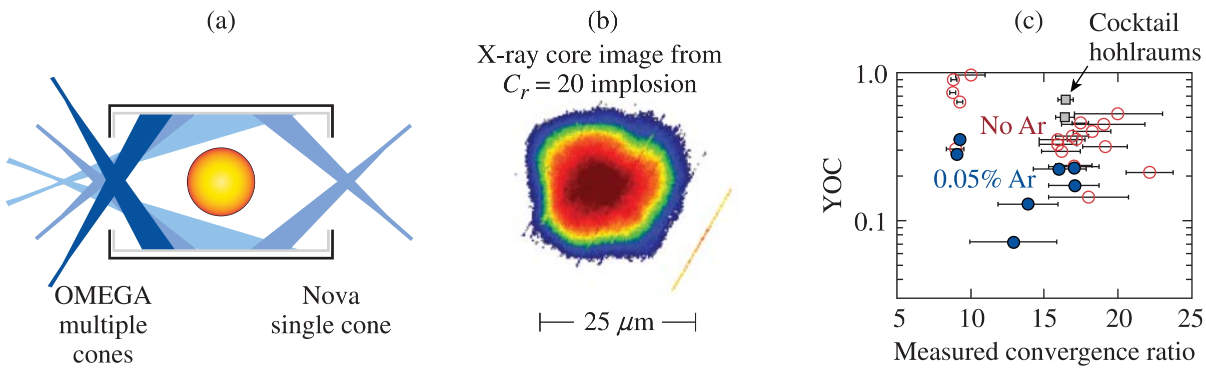
After Nova was dismantled in 1999 to make way for the NIF, the national laboratory use of the Omega facility significantly increased. In the last five years alone, the National Ignition Campaign (NIC) accounted for over 4200 target shots taken at the Omega Laser Facility.

The range of experiments conducted in collaboration with LLE's partners at the national laboratories included hohlraum dynamics experiments to improve the drive uniformity of NIF hohlraums; hohlraum energetics experiments to optimize the drive for NIF targets, opacity experiments, equation-of-state measurements, radiation flow, hydrodynamic instability experiments, diagnostic development, shock timing, ablator burnthrough measurements, laser–plasma interactions under the long-scale-length plasma conditions expected on the NIF, and many other experiments critical to the NIC and to the Stockpile Stewardship Program.

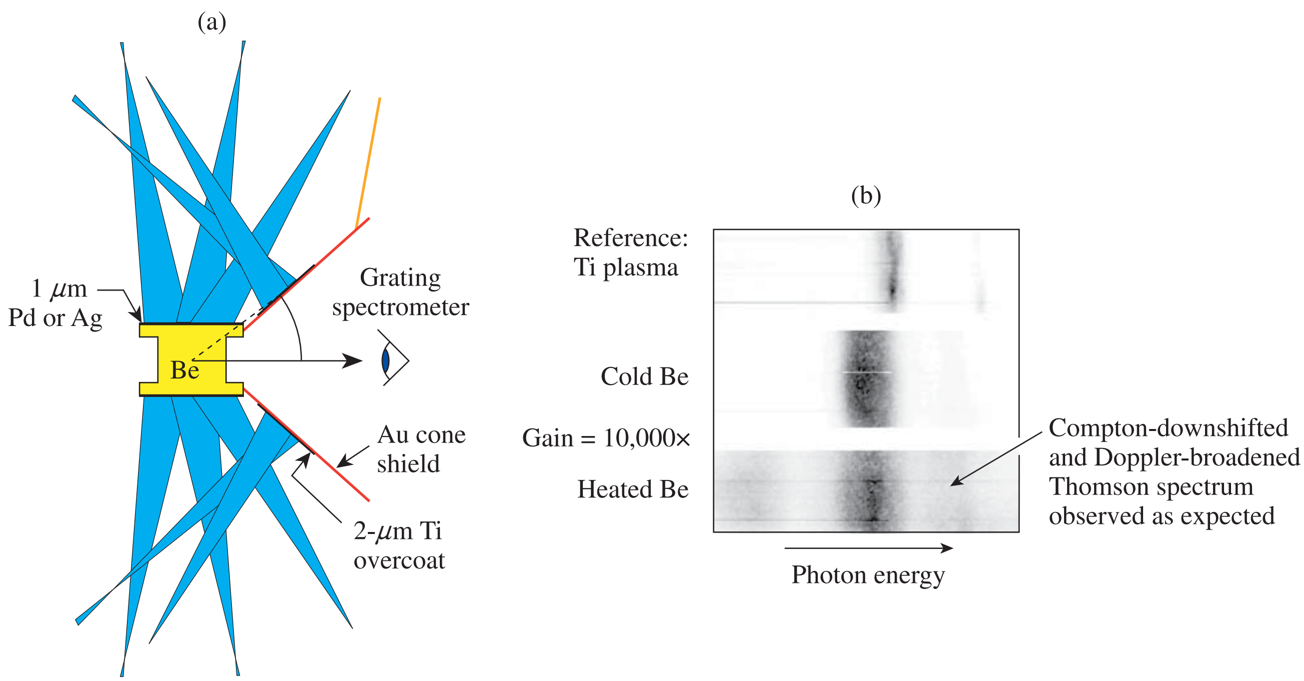
As the NIF project gained steam, the role of LLE in the project grew well beyond participation in the NIC experimental program. LLE became a major partner in both the NIF laser

The NIF is a 1.8-MJ laser facility completed in 2009. The NIF was built as a major project with four partners: LLNL, LANL, LLE, and SNL. The schematic shows the size comparison of LLE's OMEGA laser to the NIF. LLE was a principal partner in the NIF design and construction, including the production of most of the facility's large-aperture optical coatings and major participation in the National Ignition Campaign (NIC) to demonstrate ignition on the NIF—expected to be achieved in ~2011–2012.

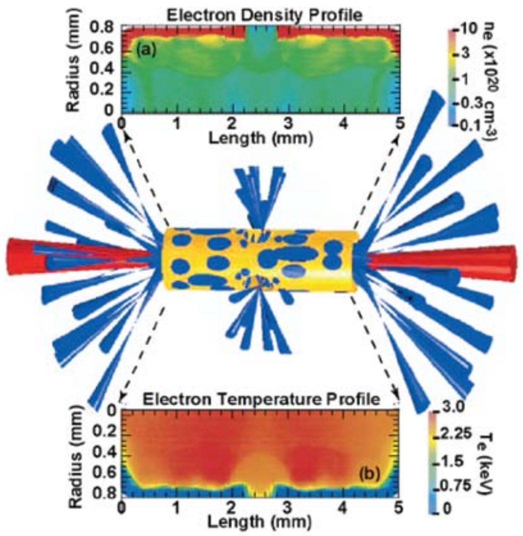




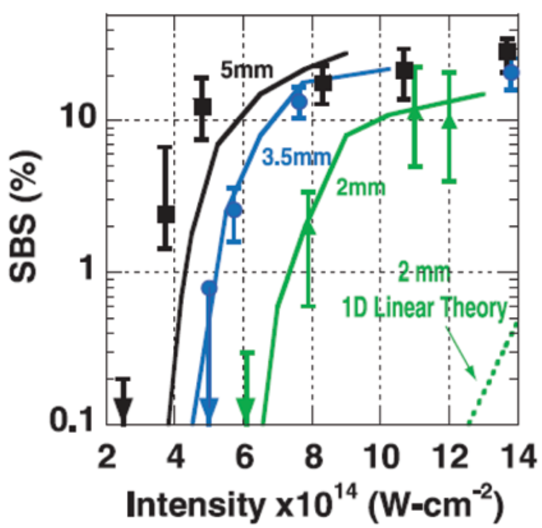
Results from indirect-drive experiments conducted in 2000 on OMEGA. (a) Schematic showing the improved hohlraum drive uniformity achieved with the OMEGA multiple-cone drive compared to that of the Nova single cone. (b) Typical x-ray image of an OMEGA implosion showing a symmetric capsule implosion with a convergence ratio of ~20. (c) Plot of the ratio of the actual neutron yield divided by the calculated 1-D clean yield (YOC) as a function of measured convergence ratio. The improved performance of the OMEGA experiments (open circles) over Nova implosions (solid circles) is ascribed to better time-dependent symmetry control and the use of dopant-free fuel.



An important diagnostic development on OMEGA occurred when LLNL scientists [99] demonstrated, for the first time, x-ray Thomson scattering as a temperature and density diagnostic for dense plasma.



Configuration of an experiment conducted by Froula et al. *(LLNL) [100] to measure laser–plasma interactions in long-scale-length NIF-like plasmas. The 5-mm-long hohlraum used in this experiment was irradiated with 51 OMEGA beams and used one the OMEGA beams as a probe: propagating down the axis of the hohlraum along a relatively uniform density plasma plateau of density 5×10^{20} cm^{-3} and electron temperature ~2.5 keV.*



Stimulated Brillouin scattering (SBS) results from the long-hohlraum experiment showing the percentage of SBS as a function of beam intensity for several different plasma lengths. The solid curves are predictions obtained from the SLIP code. For reference, a curve (dashed) is shown that was calculated using linear theory for the 2-mm-long case where an SBS gain of ~11, for an intensity of 1×10^{15} W/cm^2, is determined by postprocessing the hydrodynamic properties.

project and the NIC campaign. Captain Loucks was appointed as the Principal Deputy for NIC. In addition to providing many of the optical components for NIF during NIF construction, LLE has taken a major role in the development of the cryogenic systems for the NIF and many of the ignition diagnostics including neutron diagnostic systems.

Edward Moses is the Principal Associate Director for NIF and Photon Sciences at LLNL. He joined LLNL in 1980 and became the program leader for laser isotope separation and material processing and Deputy Associate Director for Lasers. From 1990 to 1995 he was a founding partner of Advanced Technology Applications. He returned to LLNL in 1995.

The CEA Connection

In recent years, the Commisariat à l'énergie atomique et aux énergies alternatives (CEA) of France and the Atomic Weapons Establishment (AWE) of the United Kingdom have become regular users of the Omega Laser Facility. In particular, in 2010 CEA and LLE co-celebrated the tenth anniversary of collaborative experiments at the Omega Laser Facility and jointly published a volume dedicated to that collaboration [101].

The results from using the OMEGA laser have demonstrated remarkable success during the past ten years, leading to fruitful interactions between CEA and the U.S. DOE–National Nuclear Security Administration (NNSA). The U.S.–France collaboration in the field of experimental laser–matter interaction physics reaches back more than 20 years with the first shots on the Nova Laser at LLNL and the Phebus laser at the Limeil–Valenton CEA Centre in France. Experiments on Nova, in close cooperation with LLNL and LANL, produced results that contributed to showing that ignition was feasible in megajoule-class lasers; therefore, the NIF and the Laser Megajoule (LMJ) programs could begin.

With NIF and LMJ in design and construction, the shutdown of Phebus and Nova in 1999 raised the issue of maintaining competent teams and facilities aimed at studying the design of future targets to reach ignition. In the U.S., the response was to use the Omega Laser Facility. DOE decided to continue its collaboration with CEA beyond the planned shutdown of Nova through joint experiments at LLE.

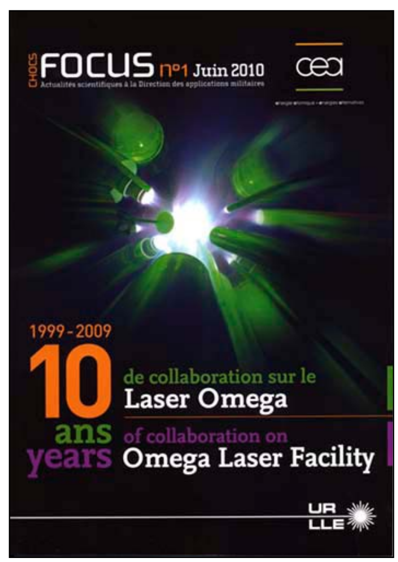
Since the first shot on OMEGA over a decade ago, more than 500 successful CEA–LLE shots have been performed at the Omega Laser Facility, thanks to the use of resources specific to CEA (targets, diagnostics, and principal investigators) and LLE teams. The CEA Experimental Program at LLE has extended the topics studied on Nova, such as laser–plasma interaction, x-ray conversion, implosion symmetry, and hydrodynamic instabilities. The first experiments were performed with U.S. targets and diagnostics, making it possible for CEA, after the closing of Phebus, to continue to train their teams in target fabrication, validation of diagnostics, and the control of experiments at a large laser facility.

Because modeling the relevant phenomena responsible for the conversion of laser power to x-ray power is complex and yields uncertainties in the simulations, the first CEA experiments carried out on OMEGA had the following goals: (i) x-ray conversion experiments in open geometry to benchmark numerical simulations and (ii) indirect-drive experiments to assess the performance of hohlraums that were used on subsequent experiments to characterize implosion symmetry or hydrodynamic instability growth. The OMEGA laser, which delivers very uniform irradiation on spherical targets, makes benchmarking numerical simulations easier and more relevant by minimizing 2-D effects; the laser geometry also minimizes the influence of self-generated magnetic fields, which may affect electron transport. The first indirect-drive experiments in 2001 tested cylindrical hohlraums for implosion symmetry studies. They were followed in 2003 by comparisons between cylindrical and "rugby-shaped" hohlraums. The influences of gas fill on drive and wall blow-off motion were investigated later.

Recent experiments have validated hohlraum performance at radiation temperatures above 250 eV, approaching drive temperatures for LMJ ignition target designs.

For the past decade, CEA has developed, produced, and delivered more than 500 targets to the Omega Facility. Many of the laser experiments have allowed for the development of important expertise in target component fabrication, assembly, and implementation. For example, hohlraums for x-ray conversion, an element of many experiments on OMEGA, are often carried out using cylindrical hohlraums made of two layers (plastic-coated gold) or sometimes of very small thicknesses (a few micrometers) of other elements (titanium, copper, and germanium). A succession of specific techniques (polymeriza-

CEA scientists on site in 2009 during a series of experiments to develop nuclear diagnostics. From left to right: Jean-Luc Bourgade (CEA point of contact at LLE), Michel Barbotin, Didier Brebion, Tony Caillaud, Henri-Patrick Jacquet, Olivier Landoas, Julien Gazave, and Bertrand Rosse.



In 2010, CEA and LLE jointly published a special volume to commemorate the 10th anniversary of collaborative experiments at the Omega Laser Facility.

tion, machining, vacuum deposition, and mandrel removal) has been successfully implemented in manufacturing these hohlraums. These technologies and the expertise developed for more than ten years at CEA, particularly for the experimental studies carried out on OMEGA, have paved the way for future targets for the LMJ program.

Theoretical Work in the 1990s

Of particular importance to fusion, as well as to other experiments involving the use of high-power lasers for high-energy-density physics experiments, is the interaction between the incident laser energy and the plasma resulting from the interaction of this radiation with a particular target. Plasma instabilities can result that can be very disruptive because they can lead to the generation of unwanted suprathermal electrons and/or the loss or redistribution of laser energy that would otherwise be coupled into the target. During the 1990s, progress was made in several areas of the investigation of the plasma physics of laser-driven plasmas including the use of systematic perturbation methods to derive formulas for the Landau damping rates of electron-plasma waves and ion-acoustic waves [102]; calculations of the damping of localized plasma waves that avoided the introduction of complex particle velocities [103]; calculations of the power transfer between crossed beams—this phenomenon has applications to the hohlraum irradiation geometry [104]; and experimental measurements of stimulated Brillouin scattering in long-scale-length laser plasmas [105].

Most high-energy-density systems involve the application of energy to some initial configuration of matter so as to assemble it into some other state (usually a higher-energy state). Hydrodynamic instabilities limit the ability to achieve high energy density. During this period, important efforts were initiated to improve our theoretical understanding of hydrodynamic instabilities. These efforts were led by some of the newer colleagues that McCrory had recruited into the University by this time [106–108].

The capsule-design effort at LLE in the mid-1990s had three main objectives: (1) to model the physical processes occurring in direct-drive experiments; (2) to develop and optimize designs of future direct-drive experiments; and (3) to develop and optimize designs for direct-drive NIF and ICF reactor conditions.

Three hydrodynamic computer codes were used in this effort. The one-dimensional (1-D) Lagrangian hydrodynamics code *LILAC* was used to simulate the ideal case of uniform laser irradiation. It is the primary code used at LLE for

An important contributor to the LLE theoretical program for nearly three decades is Dov Shvarts of Ben Gurion University and the Nuclear Research Center, Negev, Israel. As a visiting scientist, Dov has authored or co-authored 50 LLE papers on topics ranging from UV laser–matter interaction to the modeling of cryogenic target implosions. Shvarts' expertise is particularly significant in the field of unstable hydrodynamics. He was awarded the Edward Teller Medal in 1999 for "Completely changing the understanding of three-dimensional simulations through his work in hydrodynamic instabilities."

target design and the modeling of implosion experiments. At its core is a hydrodynamics model that treats the plasma as a two-temperature (ions and electrons), single-velocity fluid. In addition, *LILAC* includes the following physics: flux-limited thermal electron transport [19,109]; inverse-bremsstrahlung absorption; radiation transport with LTE and non-LTE atomic physics options; thermonuclear reactions and the transport of their primary charged particles; suprathermal electron transport; and a choice of equations of state, including *SESAME* [110], analytic Thomas–Fermi using Bell's formulation [111], and ideal gas.

The effects of irradiation nonuniformities and capsule imperfections were examined with the two-dimensional (2-D) Lagrangian radiation-hydrodynamics code *ORCHID*. *ORCHID* models the hydrodynamics of the plasma as a single fluid with the two-temperature approximation for electrons and ions. Thermal transport is solved using flux-limited diffusion employing Spitzer and Braginski [112] coefficients for the electron and ion thermal conductivities. Multigroup flux-limited diffusion is employed to solve both radiation transport (using LTE or non-LTE opacity tables) and the transport of thermonuclear-burn reaction products. *ORCHID* has the option to use any of the three equation-of-state models used for *LILAC*. Laser deposition is simulated using inverse bremsstrahlung with ray tracing.

ORCHID has been routinely used to calculate the growth of the ablative Rayleigh–Taylor instability, seeded by nonuniform laser irradiation or outer-surface target imperfections.

Long-scale-length plasma-physics experiments were designed and analyzed using the 2-D Eulerian hydrodynamics code *SAGE* developed by Craxton and McCrory in the late 1970s [113,114]. Similar to the other LLE codes, *SAGE* includes a flux-limited diffusion model for thermal conduction, ideal-gas and *SESAME* equations of state, a multigroup flux-limited diffusion treatment of radiation transport, and inverse-bremsstrahlung laser absorption. The hydrodynamics are modeled using the flux-corrected transport (FCT) algorithm of Boris and Book [115].

In the late 1990s, LLE began to develop a new multidimensional hydrodynamics code *DRACO*, which is now a workhorse at the Laboratory and can run one-, two-, and three-dimensional simulations using an Arbitrary Lagrangian Eulerian (ALE) hydrodynamics formulation and, where possible, common physics routines. *DRACO* is capable of running on massively parallel computing hardware. *DRACO* has advanced rapidly and now supports planar, cylindrical, and spherical geometries in one and two dimensions and planar geometry in three dimensions. It is currently the principal design tool of all multidimensional hydrodynamics experiments conducted at the Omega Laser Facility.

During the 1990s the LLE theoretical design group developed some of the concepts that are the basis of direct-drive capsule designs for the NIF. An important objective of OMEGA experiments is to address the key physics issues of hydrodynamic stability for direct-drive capsules. Of particular interest for OMEGA are "hydrodynamically equivalent" capsules, defined as capsules whose physical behavior scales to that of capsules appropriate for the NIF. On the basis of hydrodynamics behavior alone, the laser parameters and the capsule radius (R) would scale according to the following relations: energy ~ R^3, power ~ R^2, and time t ~ R. Although this scaling is not strictly valid, it served as a starting point for the development of 30-kJ designs for OMEGA that were hydrodynamically equivalent to the NIF baseline cryogenic-capsule, direct-drive design. Comparing the performance of NIF capsules with that of the energy-scaled implosions using ~30 kJ of incident UV laser light, 1-D simulations showed that these capsules had a similar number of Rayleigh–Taylor e foldings during both the acceleration and the deceleration phases of the implosion, similar hot-spot convergence ratios (in the range of 20 to 25), and similar implosion velocities. For 30-kJ scaled designs having $\rho R < 0.3$ g/cm^2, the hot-spot radius is defined as the radius at which the ion temperature is a fraction $1/e$ of the peak (central) ion temperature.

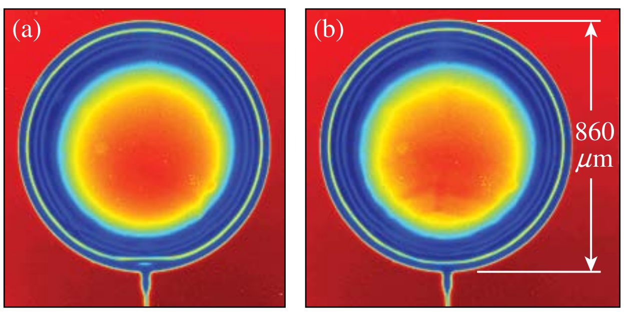
The requirements on the capsule surface finish and the initial laser imprinting for the 30-kJ OMEGA designs are more stringent than those for the NIF. For a given Fermi adiabat α (defined as the ratio of the fuel pressure to the Fermi-degenerate pressure), the actual overdense shell is a factor of ~3.7 thinner for the OMEGA design since the in-flight aspect ratios are equal for the two designs. Therefore, if the initial perturbation spectrum and the number of Rayleigh–Taylor e foldings are the same for the two capsule designs, the percentage of the overdense shell mixed during the acceleration phase (and the resulting feedthrough to the inner surface) will be higher for the 30-kJ case. In fact, 2-D simulations showed that the 30-kJ designs were approximately a factor of ~2× more restrictive in the level of initial perturbations they could tolerate than the NIF-scale ignition targets. Similarly, the smoothing time required of schemes such as SSD should scale roughly as the laser pulse length, again making the requirements for the NIF less restrictive than those of OMEGA.

Cryogenic Target Handling System

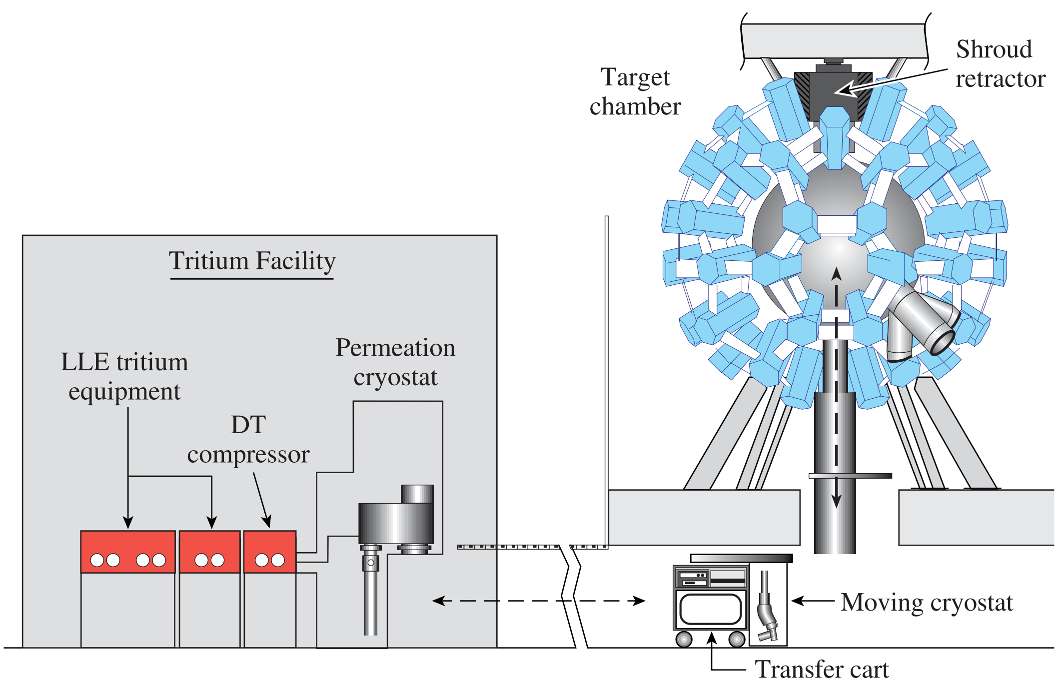
Prior to FY94, the LLE Target Fabrication Group was solely responsible for providing all targets for OMEGA experiments. During FY94, this responsibility was increasingly transferred to General Atomics (GA), the DOE-designated target fabrication contractor for the U.S. ICF program. Currently, LLE orders targets from GA and then prepares them for experiments (including DT filling in the LLE Tritium Fill Station). LLE also builds other types of nonimplosion targets in-house. Delegating some of the target-production activities to a contractor allowed LLE to concentrate on developing those aspects of target-production capabilities that are unique to the LLE requirements, such as direct-drive cryogenic capsules. Beginning in the early 1990s, GA, in collaboration with LLE and LANL, began work on designing a new cryogenic target handling system to support hydrodynamically equivalent cryogenic target experiments on OMEGA. These targets required very thick (~100-μm) DT layers in very thin (~a few microns) polymer containers, with extremely tight uniformity specifications [116]. The key system requirements for the OMEGA Cryogenic Target Handling System (CTHS) were to fill as many as 12 targets per week at gas pressures as high as ~1500 atm, with cryogenic layer uniformity controlled with either beta layering or other D_2- or DT-ice smoothing techniques. The target had to be placed within 5 μm of target chamber center, and the cryogenic protective shroud had to be retracted, in a predetermined manner, <100 ms prior to the shot. Work on this system began in 1992 and the initial design was completed and delivered to LLE in 1999. A schematic of the OMEGA CTHS is shown below.

Significant additional work was required at LLE to complete the development of the CTHS to the required level of precision and ice-layer smoothness. In recent experiments using ~17 to 23 kJ of UV laser energy with a beam-to-beam energy imbalance of less than ~5% rms and full beam smoothing, performance near 1-D hydrocode performance has been measured with high adiabat drive and near 2-D performance has been attained with a low-adiabat drive [117]. The system began its first series of DT target experiments during FY06.

In 2008, LLE passed a major DOE milestone: Direct-drive cryogenic targets with design characteristics similar to those that will eventually be used to demonstrate ignition on the NIF were successfully compressed to an areal density (i.e., density × radius) of 200 mg per square centimeter [118]. These targets achieved a compressed fuel density of over 500× that of liquid deuterium (approximately 4× the density achieved in the first LLE cryogenic experiments in 1989). This was a major step toward demonstrating the validity of direct-drive–ignition NIF targets. The high-density target campaign was led by David Meyerhofer (LLE Deputy Director and Director of the Experimental Division), Craig Sangster (Group Leader of the OMEGA Experimental Group), and Valeri Goncharov (Theory Group Leader). Contributions to this effort were made by nearly everyone in the Laboratory. Key to this effort are the contributions of the LLE Target Fabrication Group led by David Harding and the LLE Cryogenic and Tritium Facility operated under the leadership of Roger Janezik and the excellent engineering effort provided by the LLE Engineering Division, now led by Douglas Jacobs-Perkins.



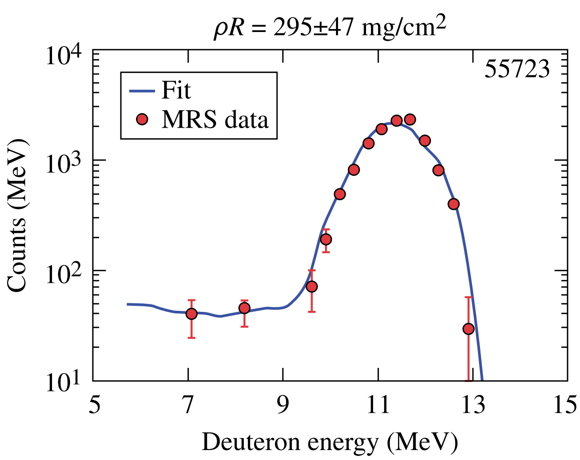
Cryogenic-DT targets make use of the beta-decay heating of the tritium to produce uniform layers of DT inside thin plastic shells. The shadowgrams (left) are used to determine the uniformity of the DT layer of a typical OMEGA cryogenic-DT target mounted on a stalk. In (a) is the target without any additional heating—note the nonuniformity at the bottom caused by the presence of the support stalk. When heat is applied to the stalk by using a low-power IR laser, as in (b), the DT-layer uniformity improves. Such techniques have been used to produce cryogenic-DT targets with DT-layer uniformity that meets the NIF specification for ignition targets.



Schematic of the OMEGA Cryogenic Target Handling System.

By 2010, the areal density of cryogenic-DT implosions had been pushed up to 300 mg/cm^2 [119]. These implosions benefitted from improvements in target fabrication, specialized plasma diagnostics, and improved target designs.

David Meyerhofer (left, LLE Deputy Director and Experimental Division Director), Craig Sangster (center, OMEGA Experimental Group Leader), and Valeri Goncharov (right, Theory Group Leader) were responsible for the OMEGA cryogenic target implosion experiments that achieved a record fuel areal density of 300 mg/cm^2 and compressed density of over 100 g/cm^3.



Scattered deuteron spectrum obtained by the magnetic recoil spectrometer (MRS) instrument (developed in collaboration with MIT) from an OMEGA cryogenic-capsule implosion that achieved a fuel areal density near 0.3 g/cm^2 [from Ref. 119]. The MRS is used to determine the spectrum of DT neutrons produced by the target. Neutrons forward scatter deuterons from a CD foil placed near the target. The MRS momentum analyzes the deuterons to produce a spectrum directly proportional to the target's neutron spectrum. The red dots correspond to the experimentally measured deuteron spectrum, and the solid blue curve is a calculated fit for an areal density of 295 mg/cm^2.

Charged-Particle Diagnostics and the MIT Connection

LLE collaboration with the MIT Plasma Science and Fusion Center (Richard Petrasso and colleagues) resulted in major accomplishments in the area of charged-particle

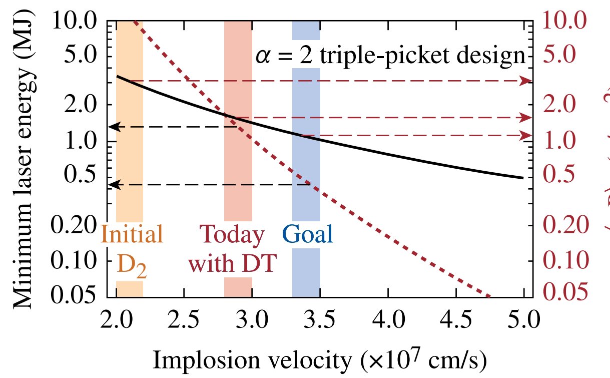
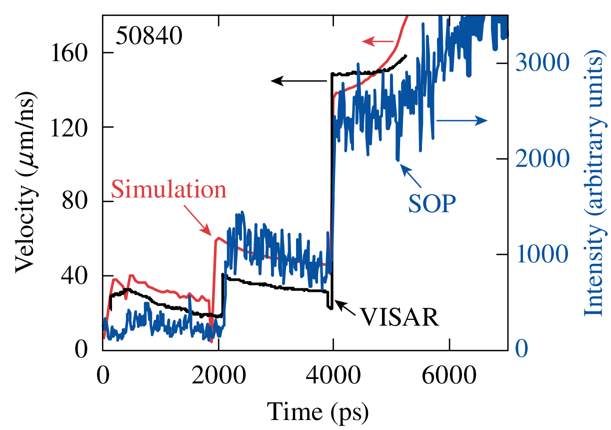


Chart showing minimum laser energy required for ignition (black curve) versus implosion velocity and the corresponding minimum areal density (red dashed curve) for an implosion with α ~ 2. Although energy-scaled experiments on OMEGA with implosion velocities of 2 × 10^7 cm/s do not scale to ignition on OMEGA, the minimum laser energy for ignition with the current energy-scaled experiments at ~3 × 10^7 cm/s is 1.5 MJ, well within the design envelope for the NIF [119].



Key to the achievement of OMEGA high-density implosions as well as the demonstration of ignition on the NIF is the precise measurement and control of timing of the shocks that coalesce to form the high-density core of an imploding capsule. This figure shows measurements of the shock velocity and timing of multiple shocks in a liquid-deuterium target performed using the VISAR (black curve) and SOP (blue curve) diagnostics on OMEGA compared to hydrodynamic code simulations (red curve) [120].

Upon the retirement of Capt. Steve Loucks, Douglas Jacobs-Perkins was appointed to the position of Director, Engineering Division. Dr. Jacobs-Perkins has made important contributions to many LLE systems including work on the 2-D SSD system for OMEGA and control system programming and operational support for LLE's cryogenic target program.

The LLE–MIT team responsible for the design and construction of the NIF MRS system shown above in its assembled configuration ready for shipment to LLNL for installation on the NIF. Kneeling in front from right to left are Daniel Casey (MIT), Michelle Burke (LLE), Tim Clark (LLE), Brian Rice (LLE); standing (left to right) Mark Romanofsky (LLE), Robert Till (LLE), Oscar Lopez-Raffo (LLE), Chad Abott (LLE), Tom Lewis (LLE), Jason Magoon (LLE), Johan Frenje (MIT), and Milt Shoup (LLE). Photos of John Szczezepanski (LLE) and Nick Fillion (LLE) are inserted upper right.

diagnostics during the 1990s. This collaboration led to the development of two magnet-based charged-particle spectrometers (CPS's) [121], a number of wedged-range-filter proton spectrometers [122], and most recently the development and implementation on OMEGA and on the NIF of the magnetic recoil spectrometer (MRS) [123]. The MRS was designed to make detailed measurements of the neutron spectrum from DT-fueled capsules and is capable of measuring the neutron spectrum from a few MeV up to 30 MeV. For near-ignition implosions, the MRS can measure the fuel areal density of DT fuel by measuring the number of high-energy tertiary neutrons—above 14.1 MeV. For near-term OMEGA implosions, the MRS can measure the compressed areal density of DT fuel by measuring down-scattered neutrons below 14.1 MeV.

Measurements of the charged-particle yield and energy spectra have yielded valuable information about target conditions in highly compressed cores (especially for the cryogenic capsule implosions). This joint charged-particle–diagnostics effort has been significantly strengthened by collaboration with Steve Padalino and the faculty and students of the State University of New York at Geneseo Physics Department.

Imprinting and Rayleigh–Taylor (RT) Experiments

Significant effort at LLE has been dedicated to understanding laser imprinting, the process whereby laser nonuniformities lead to modulations in the target. These modulations are amplified by RT instability during shell acceleration and therefore have the potential to disrupt the shell and degrade the target performance. Several experiments characterizing the imprint have been carried out [124–126].

In the course of this work, several approaches have been identified to potentially control or mitigate the effect of imprinting, including imprint reduction using intensity spikes [127]; imprint mitigation using foam [128,129]; and imprint mitigation using high-*Z* layers in a collaborative effort with NRL-led experiments on OMEGA.

Adiabat shaping using intensity pickets is a major accomplishment of LLE. It greatly increases the attractiveness of direct drive by allowing the fuel to be driven on a lower adiabat, thereby increasing target gain without increasing RT growth [130].

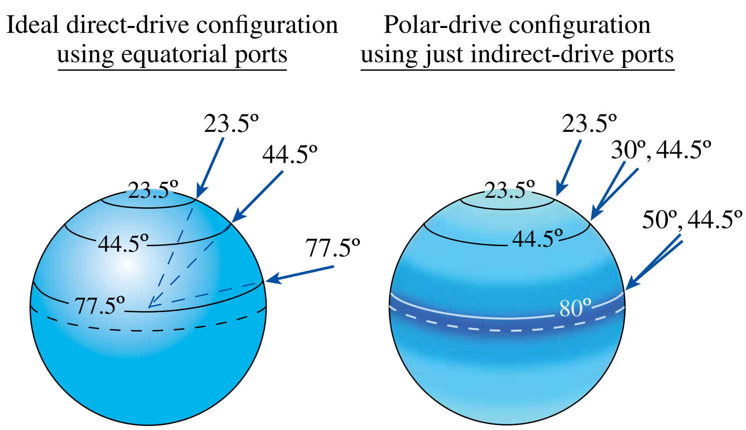
Experimental RT work on OMEGA during the past few years has focused on the more-accessible acceleration phase of the RT instability and, in particular, on measurements of the linear growth rates [131–135]. A major goal of this work has been the validation of 2-D computer modeling, which is critical for examining the effects of the less-accessible deceleration-phase instability on target designs. An extensive series of experiments was carried out on OMEGA in which the growth rate of the RT instability was measured for targets with preimposed modulations of various wavelengths. These experiments were a continuation of earlier collaborative experiments carried out on Nova using a single drive beam [136].

Seminal experiments were carried out on OMEGA to validate the reduction in the RT growth rate using a prepulse, or picket, preceding the main laser-drive pulse in planar target experiments. The data show that a high-intensity picket significantly reduces the RT growth rate for certain modulation wavelengths. These results suggest that the RT growth for short-wavelength, laser-induced imprint perturbations can be virtually eliminated by modifying the drive pulse to include a high-intensity picket on the leading edge [130,134].

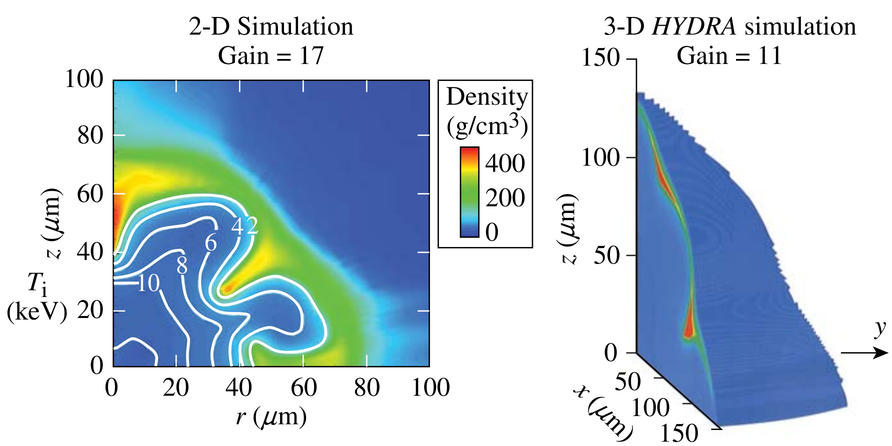
Polar Drive for the NIF

LLE's direct-drive ICF ignition target designs for the NIF rely on hot-spot ignition and consist of a cryogenic target with a spherical DT layer (possibly embedded in a foam matrix) enclosed by a very thin (~a few microns) polymer layer and irradiated by ~1.5 MJ of UV laser light in a symmetric configuration. The baseline target design for the direct-drive–ignition capsule on the NIF produces a gain of ~35 [137]. Higher gains may be possible with wetted foam shells [138,139]. The NIF, now operating at LLNL, has 192 beams arranged in a polar configuration (beams all incident between 23° and 50° from the vertical) and capable of producing up to 1.8 MJ of UV light. Since the NIF is not presently scheduled to be reconfigured to its direct-drive configuration, which includes equatorial beams incident through ports at 77.5° from the vertical, LLE has been exploring other approaches to carry out direct-drive implosions on the NIF. One possible configuration has been developed that involves the repointing of the NIF beams toward the equator (with the potential loss of some drive energy)—the polar-drive (PD) approach [140,141].

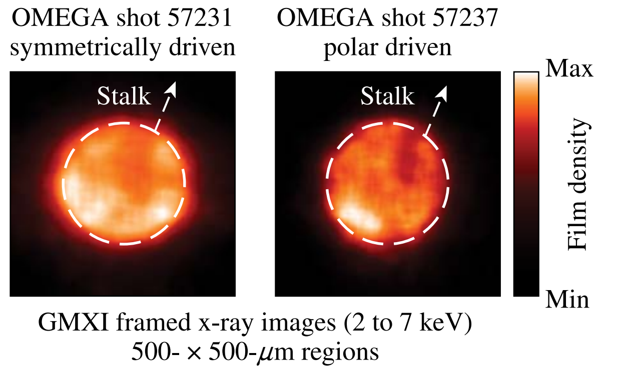
The PD approach is based on optimization of phase-plate designs, beam pointing, and pulse-shaping control. Initial 2-D simulations with PD on the NIF have shown ignition with gain.



Polar drive was devised by LLE in 2003 to conduct direct-drive implosions on the NIF without the need to reconfigure the NIF to equatorial beams. Shown on the left is the ideal direct-drive beam-pointing configuration, in which beams usually incident at 30° and 50° from the vertical enter the target chamber through ports at 77.5°. Shown on the right is the polar-drive configuration, in which all beams enter through the indirect-drive ports (at 23.5°, 30°, 44.5°, and 50°), together with the repointing required to carry out direct-drive experiments in polar-drive mode.



2-D (left) and 3-D (right) simulations of NIF polar-drive capsules show that ignition and gains of 17 and 11, respectively, are predicted for polar drive at a NIF energy of ~1 MJ.



Film-recorded framed x-ray images of implosions of DT-filled glass targets obtained with the GMXI framed x-ray imager near the time of stagnation for both a symmetrically driven target (left) and a polar-driven target (right). The target stalk direction is indicated by the dashed arrows.

Experiments are being conducted on OMEGA to validate this approach [141].

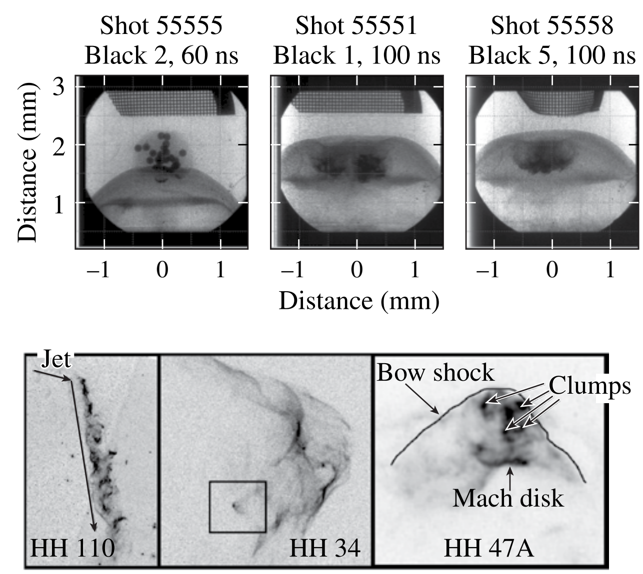
Basic Science Experiments at the Omega Laser Facility

An important part of the LLE mission is to conduct basic science experiments at the Omega Laser Facility. A part of this mission involves the management of the NLUF program at LLE. NLUF was established in 1979 to provide access to the LLE high-power laser facilities to U.S. scientists. Since NLUF's inception, 306 proposals have been submitted to use the LLE laser facilities, and, after independent peer review, 165 of these have been accepted for funding by DOE and shot time at the Omega Laser Facility. The NLUF participants have included scientists from some 40 universities, government laboratories, and private companies. Current research programs include inertial fusion, laser–matter interaction, equation of state, high-energy-density materials, laboratory astrophysics, high-energy-density plasma diagnostics development, and atomic physics. NLUF is another aspect of the LLE program that contributes to its unique position among the nation's ICF laboratories. The NLUF program is currently allotted 15% of the Omega Facility time and serves as a model for the NIF users programs to be initiated in the future.

In 2008, under DOE guidance, the basic science program was expanded to include basic science experiments (Laboratory Basic Science or LBS) conducted by participants of the national ICF program (i.e., LLNL, LANL, SNL, and LLE). A proposal solicitation for the LBS program is conducted each year, and these proposals are peer-reviewed by an independent committee of scientists. Since 2009, 61 LBS proposals have been submitted and 40 have been approved for shot time at the Omega Facility. The LBS program allocation for FY10 is 15% of the Omega Facility shots. The two basic science programs (NLUF and LBS) thus account for 30% of the Omega Facility shots at this time.

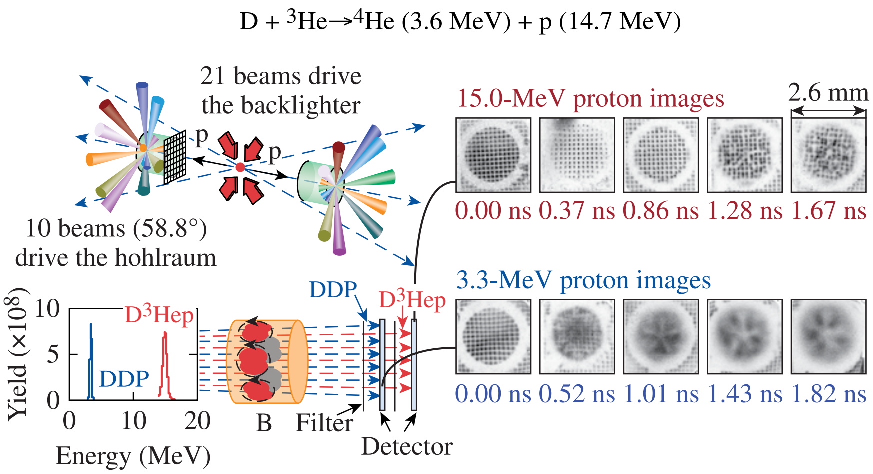
The quality and depth of the high-energy-density science that is being carried out at the Omega Facility is breathtaking. In addition to exploring some of the fundamental physics issues that underlie the inertial fusion program, the basic science experiments on OMEGA have carried out ground-breaking work in laboratory astrophysics, equation-of-state measurements, warm-dense-matter physics, fundamental laser–plasma interactions, and materials science.

The Omega Facility user community self-generated the Omega Laser Facility Users Group (OLUG) in 2009 to facilitate communication among the users of OMEGA, from the users as a group to the facility, and from the users to the broader scientific community. The group also organizes an annual workshop of facility use that is inclusive of all its members. A major purpose of the group is to focus on common desires for improvements to the capabilities and operation of the facility. Leading this effort from the start were Richard Petrasso (MIT) and Paul Drake (University of Michigan). The group now numbers 180 members from a diverse set of universities and institutions. OLUG has sponsored two workshops at LLE (2009 and 2010). More than 100 participants from 30 universities and institutions from four



The data from one series of OMEGA NLUF experiments (conducted by a team led by Rice University) showing a shock overrunning a region of clumps of matter (above) were used to obtain Hubble Space Telescope observation time to observe shocked clumps from jets in young stars (bottom) [142].

nations have attended each of these events. More than 30% of the participants have been graduate students working in the field of high-energy-density physics. The student participation has been partially sponsored by DOE/NNSA.



Under the NLUF program, the group from MIT led by Richard Petrasso conducted ground-breaking proton radiography experiments on OMEGA to investigate the electric and magnetic field structures inside hohlraums [143].

The executive committee of OLUG at its first workshop in 2009 (from left to right): R. Paul Drake [(inset) University of Michigan)], Jim Knauer (LLE), James Cobble (LANL), Richard Petrasso–Committee Chair (MIT–PSFC), Peter Norreys (Rutherford Appleton Laboratory–UK), Marilyn Schneider (LLNL), Hector Baldis (University of California–Davis), and Roberto Mancini (University of Nevada–Reno).

University of Chicago astrophysicist Robert Rosner speaks to the participants of the 2010 OLUG Workshop.

Participants of the 2010 OLUG Workshop.

OMEGA EP

In October 2001, a major enhancement to the OMEGA Laser System (now called OMEGA EP—for Enhanced Performance) was proposed to include four new high-energy beamlines, a versatile high-intensity capability, and a new auxiliary target chamber. The enhanced facility is illustrated in the figure on p. 38.

The high-intensity beams of OMEGA EP are generated using the CPA technique originally developed and demonstrated at LLE by Gerard Mourou and Donna Strickland in the mid-1980s [78]. With the CPA method, the laser pulse is stretched thousands of times, amplified, and recompressed into a very short and very intense pulse. The OMEGA EP laser intensity on target is expected to eventually reach 10^{21} W/cm^2, inducing an electric field so large that the electrons of the target material will be accelerated to a velocity close to the speed of light in a fraction of a laser cycle.

Several advanced ignition techniques will be explored at the Omega Laser Facility including "fast ignition" and "shock ignition." In fast ignition, the OMEGA 60-beam laser will compress the thermonuclear fuel to densities of hundreds of grams per cubic centimeter. The compressed fuel will then be heated to hundreds of millions of degrees centigrade by a very short burst of high energy created by OMEGA EP. The OMEGA EP pulse energy will be converted into a burst of energetic electrons when the laser interacts with the plasma surrounding the compressed fuel. These energetic electrons will deposit their energy into the cold fuel, producing a "spark" of thermonuclear reactions. In a reactor-scale fast-ignition implosion, a burn wave will then propagate from the spark throughout the fuel, causing the thermonuclear ignition of the entire fuel assembly.

LLE has recently been exploring another advanced ignition scheme—"shock ignition." The shock-ignition scheme starts with the assembly of a dense, relatively cool fuel shell. In the coasting phase of the shell implosion, a strong spherically convergent shock is launched in the shell by means of tightly focused, high-intensity laser beams. This enhances the compression of the hot spot and significantly improves the ignition conditions [144,145].

Fast ignition and shock ignition are promising paths to inertial fusion. They separate the compression from the heating and lower the total required laser energy. The fundamental physics of such advanced fusion schemes is being investigated at LLE in collaboration with the Fusion Science Center (FSC) for Extreme States of Matter and Fast-Ignition Physics co-located at LLE and co-directed by Riccardo Betti (also professor in the Mechanical Engineering Department) and David Meyerhofer.

Riccardo Betti (left) and David Meyerhofer (right) co-direct the UR Fusion Science Center (FSC) for Extreme States of Matter and Fast-Ignition Physics.

The mission of the FSC (funded by the Office of Energy Sciences of DOE) is to develop an understanding of the physics of creating extreme states of matter using a combination of high-energy drivers (compression) and high-intensity lasers (heating). The work will culminate in integrated experiments using both aspects. These experiments will be conducted at the major national high-energy-density (HED) science facilities including OMEGA EP and the NIF. The Center brings together academic scientists from around the country into a collaboration that fosters rapid progress in this exciting field. It provides support for graduate students and post-doctoral research. The study of fast ignition as a potential future energy source is a long-term goal of the Center.

It is appropriate to mention at this point that the current administrator for the Center is Margaret Kyle. Margaret, who was Don Hess's administrative assistant while he served as Vice President, has loyally served the University for over 40 years.

Upon intensive review of the OMEGA EP proposal, and with the support of the inertial fusion community and the U.S. Congress, DOE began funding this project in FY03. The project began on 1 April 2003 with $13 million in FY03 funding. The NNSA approval of "Mission Need" followed in May 2003. The University of Rochester authorized funding for an 82,000-sq-ft addition to LLE to house the new facility, located adjacent to the existing OMEGA laser. Building construction began in August 2003 and was completed in January 2005. The OMEGA EP project was completed on time and on budget and dedicated in April 2008.

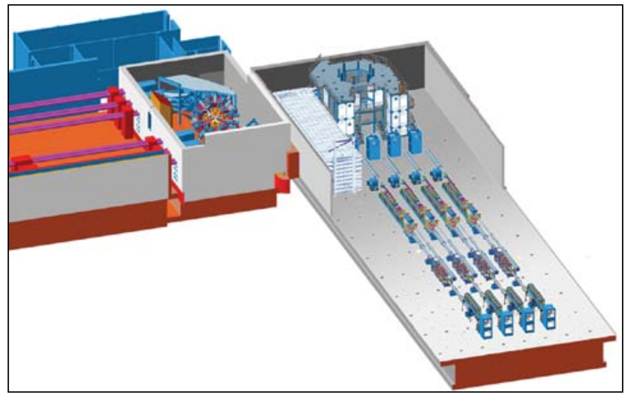
NNSA Administrator Tom D'Agostino speaking at the dedication of the OMEGA EP laser on 16 May 2008. Seated from left to right: Representative Reynolds, Senator Schumer, Representative Kuhl, and Director McCrory.

Senator Schumer speaking at the OMEGA EP dedication on 16 May 2008. Seated from left to right: UR President Seligman, Representative Reynolds, Director McCrory, Representative Kuhl, and Administrator D'Agostino.

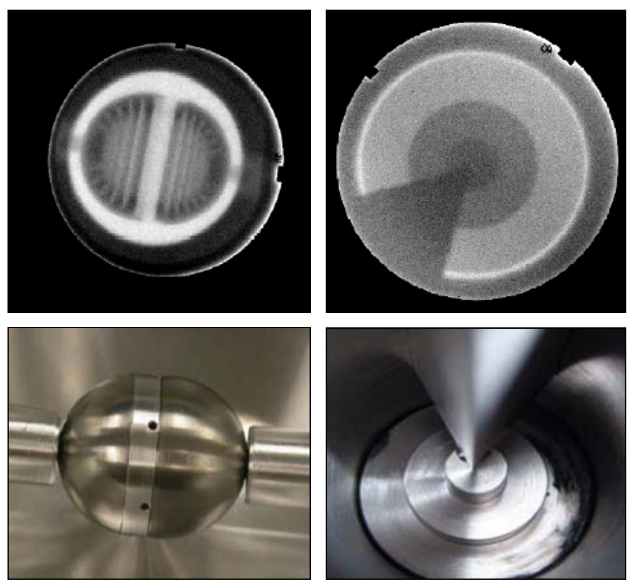
OMEGA EP couples short-pulse laser technology with the 60-beam compression facility. Since the mid-1980s, progress in laser technology has included the development of high-power, high-energy laser systems using CPA and the NIF multipass architecture. Incorporating these two technologies modernizes OMEGA and significantly expands the range of HED physics experiments that can be carried out by the LLE facilities in the future.

The four primary applications of the new OMEGA EP beams include (1) short-pulse backlighting on OMEGA; (2) fast-ignition [20] studies in the existing OMEGA chamber; (3) high-intensity and fast-ignition experiments in the auxiliary target chamber; and (4) long-pulse high-energy-density physics experiments in the auxiliary target chamber.

The value of the enhanced Omega Facility to the national high-energy-density physics (HEDP) program and inertial fusion studies is supported by a 2001 DOE report [146]. The

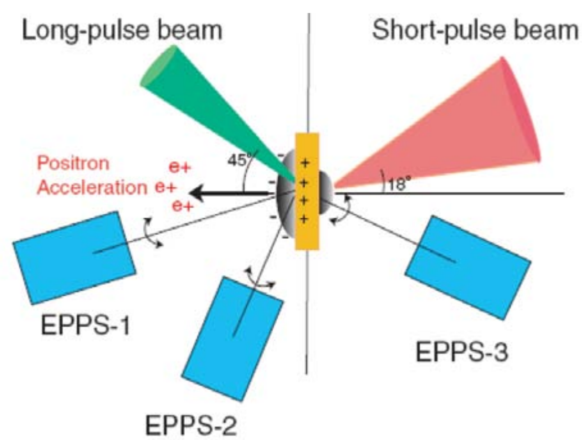


Schematic of the Omega Laser Facility. The four new OMEGA EP beamlines on the right of the figure are NIF-scale beams, with the power-amplification stage following the NIF architecture very closely with minor modifications. It is possible to inject chirped pulses into two of the beamlines for subsequent compression to short, high-intensity pulses with widths ranging from 1 to 100 ps. A switchyard in the central portion of the figure enables two of the beams to be delivered to the OMEGA target chamber, temporally compressed to high intensities using large-aperture gratings within a large compression vessel. In addition, it is possible to route all four beams to the new target chamber, with up to two temporally compressed.

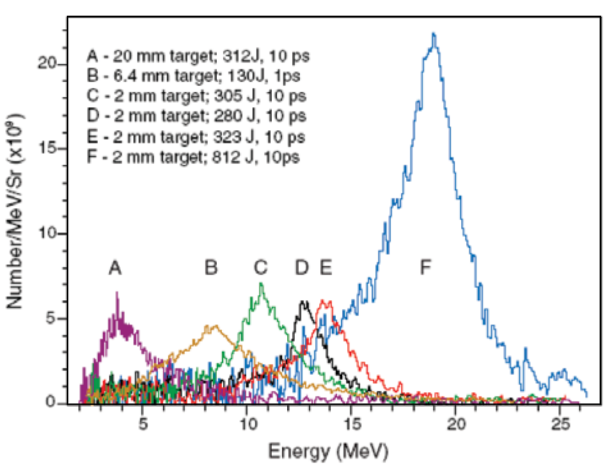


The radiography of massive objects with high-resolution MeV-photon imaging was demonstrated by a collaborative team led by CEA in 2010 OMEGA EP experiments. On the left are the test objects named "flower" (bottom) and its radiographic image (top); on the right are a step-wedge object named the "tower of Hanoi" (bottom) and the resulting radiography image (top). These images were produced using a single OMEGA EP beam operating at ~1 kJ in <10 ps.

report notes that OMEGA and the Z pulsed-power facility at SNL are the two principal facilities that are currently being used for the HEDP Program. The facilities are complementary and will serve as staging facilities for the NIF. This study highlighted a potential problem of the oversubscription of NIF experimental time and the central importance played by high-energy backlighting beams to generate x-ray images of SSP experiments. This report reiterated the importance of thermonuclear ignition in the laboratory for the SSP and the nation. Advanced ignition concepts such as fast ignition and shock ignition could provide higher energy gain on the NIF for advanced SSP experiments. In addition, fast ignition could potentially increase the utility of high-energy lasers and *Z* pinches for fusion power generation.



OMEGA EP experimental configuration used by Hui Chen (LLNL) and collaborators to produce a monoenergetic beam of positrons. The short-pulse beam strikes the front of a 1-mm-thick solid gold target with energy of ~900 J in ~10 ps. A long-pulse beam irradiates the back of the target with an ~3-ns-long pulse delivered ~2-ns prior to the arrival of the short pulse. Positrons generated within the target are accelerated by an electron sheath formed on the rear of the target.



Positron spectra produced by lower-energy experiments (A–E) on the LLNL Titan laser and by an 812-J, 10-ps laser pulse on OMEGA EP (F) [147].

From its initial operations, OMEGA EP has produced exciting new results in high-energy-density physics including record yields of positrons produced when a high-intensity short-pulse beam interacts with a high-*Z* target, short-pulse Compton radiographs of imploding high-density targets, and copious high-energy x-ray production for short-pulse radiography applications.

Advanced Optical Technology and Science

Underpinning much of the success of LLE over the first four decades has been the strong foundation in optical science and technology that characterizes the University of Rochester and the Rochester metropolitan area.

The Optical Materials Technology Group under the leadership of Dr. Stephen Jacobs within the Engineering Division has developed world-class research and development capabilities over the years in liquid crystal optics [148–151], laser damage testing [152–161], high-power optical coating [162–170] (within the Optical Manufacturing Group), and an optical fabrication shop used for fabricating specialized optics and as a student teaching facility [171]. This group, working with the Center for Optical Manufacturing (COM) of the UR, helped bring magnetorheological finishing (MRF) to fruition [172–175]. The Optical Materials Technology Group received the R&D 100 Award in 1989 for its development of the liquid crystal polarizer.

Computer numerically controlled (CNC) finishing did not exist for most optics until COM (including its LLE partners) and its industrial collaborators invented, patented, and com-

Stephen Jacobs (foreground) shown working in the laboratory during the development (~2006) of improved MRF techniques applied to polymer finishing.

mercialized the MRF process. As exemplified by a line of MRF machines sold by QED Technologies of Rochester, NY, the MRF process is capable of rapidly polishing out and figuring a variety of materials from a few millimeters to over 1 m in diameter. Plano, spherical, aspherical, and cylindrical optics with round or non-round apertures may be finished to better than 0.1-μm peak-to-valley form accuracy in minutes with a resulting surface microroughness of <1-nm rms. The MRF process is key for many NIF optics.

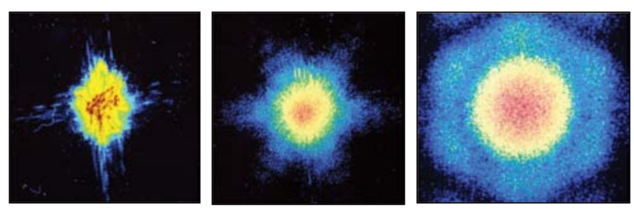
Amy Rigatti is head of Optics Manufacturing (OMAN) at LLE. She manages the activities of a group of ~25 engineers and technicians who are responsible for the design, acquisition or manufacture, testing, installation, and maintenance of almost all the optics used on OMEGA and OMEGA EP. Amy is also responsible for managing contract work with outside organizations including LLNL in California and CEA in France. The group has produced many of the large-aperture optics for the NIF laser and other high-power facilities around the world.

The Optical Imaging and Science Group headed by Terry Kessler within the Experimental Division has specialized in developing a variety of diffractive optics capabilities including research and development on phase converters, high-efficiency and high-damage-resistance gratings, and a variety of other diffractive optics devices.

One of the early manifestations of this work was the 1987 deployment on Nova of LLE binary DPP's. These diffractive optics demonstrated the importance of this technology to the LLNL indirect-drive program. In 1992, LLE designed and fabricated fully continuous DPP's using microlithography. Today's NIF continuous-contour phase plates (CPP's) are fabricated using the MRF technology developed by LLE and COM.

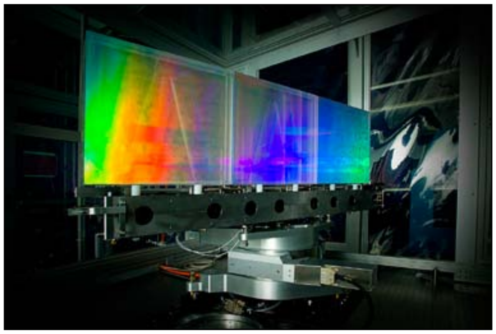
Together with local industry, LLE designed and fabricated the first diffractive color corrector (DCC), which compensates the accumulated chromatic aberration in a large, multipass laser system such as OMEGA EP. The diffractive surface is a patterned, polymeric coating that is placed on the middle optical

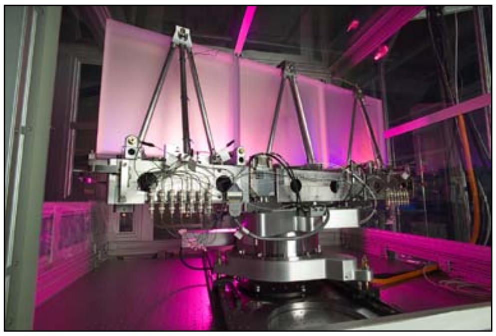
Terrance Kessler was responsible for the development and implementation of phase conversion on OMEGA and leads the Optical and Imaging Sciences Group at LLE. A major part of this group's current work is to develop diffractive optics for high-power-laser applications.



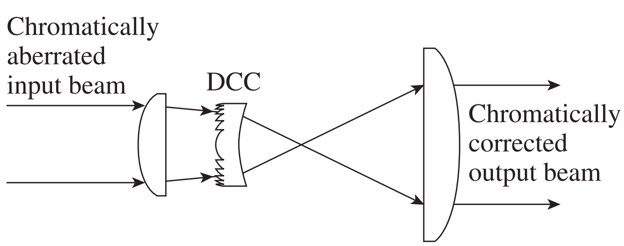
The 1987 demonstration of the effect of DPP's on the Nova beams. Left: the Nova beam at best focus without any phase conversion. Center: Nova beam phase converted with a DPP designed for indirect-drive targets. Right: Nova beam with a direct-drive DPP.

Amy Rigatti (center) and James Oliver (far right) hosted a visit by CEA scientists and engineers working on optics for the LMJ facility in France.





LLE's tiled-grating assembly (TGA) is the first tiling assembly used on a petawatt-class laser system. The OMEGA EP gratings have an overall aperture of ~1.5 m and can produce near-diffraction-limited performance.



Schematic showing the use of a diffractive color corrector (DCC) to compensate for axial chromatic aberration accumulated through the OMEGA EP Laser System. The corrector is the second element of the Keplerian telescope used to expand the OMEGA EP beam, with a diffractive lens on its flat surface.

element within a beam-expanding telescope. The DCC provides smaller focal spots and shorter pulse widths, thereby increasing the focal plane irradiance by nearly an order of magnitude.

Education and Interactions with University Faculty

Many students educated at LLE have made significant contributions to the DOE Inertial Fusion Program, both during and after their research activities at LLE, and some now hold positions within the national laboratories. In addition, many LLE graduates have made important scientific contributions at universities and in industrial research. The University remains committed to a strong educational mission for the Laboratory.

A cornerstone of LLE's education and training activities is collaboration with faculty from the University of Rochester, representing many departments and programs including Mechanical Engineering, The Institute of Optics, Physics and Astronomy, Electrical and Computer Engineering, Chemical Engineering, Materials Science, Computer Science, and the University's Medical Center. These collaborations benefit LLE in two ways: by adding to LLE's base of expertise and by providing LLE with access to graduate and undergraduate students.

Currently 85 students are performing graduate research work at the Laboratory, of whom approximately half are funded directly by the Laboratory. The graduate program is strengthened by the involvement of more than 20 faculty members who represent a broad range of departments and programs within the University. In addition, students and faculty members from external institutions benefit from the LLE program through direct collaborative programs and through the NLUF. A total of 191 students have received their Ph.D. degrees based on work at the Laboratory since LLE was founded in 1970. More than 100 graduate students at other institutions have conducted Ph.D. research work via the NLUF program at the Omega Laser Facility.

Undergraduate students from the University of Rochester and the State University of New York at Geneseo and co-op students from the Rochester Institute of Technology are employed to work in various areas at LLE, including diagnostic development, data analysis and reduction, materials and optical-thin-film–coating laboratories, programming, and image processing. This is a unique opportunity for the students, many of whom have gone on to higher degrees in the areas in which they worked or have found employment in these areas. Approximately 60 undergraduate students receive research experience annually at LLE.

In 1989 LLE began a summer research program for high school students who have completed their junior year. The goal of this program is to excite the students about careers in the areas of science and technology by exposing them to research in a state-of-the-art environment. Currently 14 to 16 students spend eight weeks working full-time on individual projects supervised by LLE staff members. Several students from the program have appeared as authors on LLE publications and conference presentations. The program has produced 28 semi-finalists and 4 finalists for the Intel (formerly Westinghouse) and Siemens-Westinghouse Science Talent Competitions. Many of the students proceed to major in science-related disciplines at nationally recognized universities, and several are currently working toward a Ph.D.

Marshall Rosenbluth (second from right) is pictured here in 2002, a year before his death, on one of his many visits to LLE. Rosenbluth, known affectionately as the "Pope of Plasma Physics," began his career at Los Alamos as the leader of the group that developed the hydrogen bomb and also started his life-long quest to develop fusion energy as a viable energy source. He was a strong supporter of LLE and his own son, Alan, did his Ph.D. dissertation research at the Laboratory in the early 1980s. Rosenbluth is pictured here with Robert McCrory (right), Adrian Melissinos (second from the left), and David Meyerhofer (left).

The Laboratory maintains close relationships with the University faculty. Many faculty members currently hold or have previously held joint appointments with the Laboratory, including Adam Frank (Physics and Astronomy), Albert Simon (Mechanical Engineering), Adrian Melissinos (Physics and Astronomy), Larry Helfer (Physics and Astronomy), Joseph Eberly (Institute of Optics and Physics and Astronomy), Hugh Van Horn (Physics and Astronomy), Robert Knox (Physics and Astronomy), Phillippe Fauchet (Electrical and Computer Engineering), Chuang Ren (Mechanical Engineering), John Lambropoulos (Mechanical Engineering), Hong Yang (Chemical Engineering), Lukas Novotny (Institute of Optics), Wayne Knox (Institute of Optics), Govind Agrawal (Institute of Optics), James Fienup (Institute of Optics), Hui Wu (Electrical and Computer Engineering), Matthew Yates (Chemical Engineering), Mitchell Anthammaten (Chemical Engineering), Thomas Brown (Institute of Optics), Shaw H. Chen (Chemical Engineering), Thomas Jones (Electrical and Computer Engineering), and Roman Sobolewski (Electrical and Computer Engineering).

In addition, many LLE scientists hold or have previously held joint appointments with University Departments, including Robert McCrory (Mechanical Engineering and Physics and Astronomy), David Meyerhofer (Mechanical Engineering and Physics and Astronomy), Riccardo Betti (Mechanical Engineering and Physics and Astronomy), Stephen Jacobs (Institute of Optics and Chemical Engineering), William Donaldson (Electrical and Computer Engineering), Wolf Seka (Institute of Optics), David Harding (Chemical Engineering), Valeri Goncharov (Mechanical Engineering), Andrei Maximov (Mechanical Engineering), and John Marciante (Institute of Optics).

Dr. Steven Koonin, Undersecretary for Science of the U.S. DOE, has played an important role in the development of the U.S. ICF program through his past leadership of the National Academy of Sciences' reviews of the program. He is shown here during a recent visit to LLE as he engaged in a discussion with graduate students Maria Alejandra Barrios (left) and Lan Gao (right) during a luncheon meeting with graduate students and young scientists at LLE. Dr. Koonin has shown a strong interest in the development of inertial fusion energy as an alternative energy source for the nation.

Nuclear Fusion at LLE: The Future

With the advent of the NIF and the expectation of an ignition demonstration on the NIF laser within the next few years, it is appropriate to consider what may be in store for LLE in the future. There is no doubt that the viability and productivity of the LLE facility with its world-class laser facilities and scientific personnel could continue to grow for the indefinite future, continuing its focus on a broad range of HEDP research topics and on a broad-based education mission. The Laboratory, however, has never had a propensity to sit on its laurels. On the contrary, LLE's defining characteristic is to literally reach for the stars. Clearly, the most important mission that LLE could undertake in the wake of an ignition demonstration on the NIF is to work toward the development of inertial fusion energy as an alternative, safe, and inexhaustible energy source.

For mankind, the search of a sustainable energy source is existential. Human development and increased prosperity mandate an increasing availability of primary energy. Some estimates of the global energy requirements are that the primary energy demand will grow from ~10 Gigatons of oil equivalent (Gtoe) per year to 25 Gtoe by 2050 and that by the end of this century the demand may be ~50 Gtoe.

Today, fossil fuels account for 80% of the global energy demand. By 2008, the atmospheric CO_2 concentration had risen to 385 ppm, 38% above the concentration at the start of the industrial revolution (280 ppm in 1750). Carbon-free nuclear energy accounts for 16% of world electricity production (21% of U.S. electricity production). Only 0.4% of the world's energy demand is produced by wind, solar, or geothermal energy.

To stabilize the world's carbon dioxide production will require not only significant improvements in energy efficiency and use but also the development of substantial new energy technologies beyond 2030.

Nuclear fusion provides an attractive alternative for a large primary energy source. Its advantages over other approaches are significant:

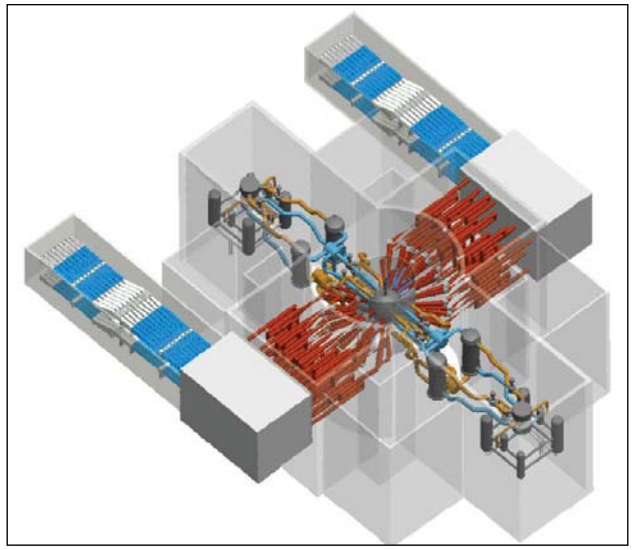
- Virtually inexhaustible energy
- Relatively low safety hazards (~1/1000 of radiation produced by fission plants)
- No greenhouse gas emissions
- Range of power plant sizes possible
- Potential for economically competitive designs

Conceptual inertial fusion power plant designs have already been developed. A laser-driven power plant would require a system with the following general characteristics:

- Laser wavelength: ~0.35 μm
- Energy per pulse: ~1 to 5 MJ
- Repetition rate: 5 to 15 Hz
- Laser efficiency: >10%
- Target fusion gain: >100

Without doubt, the challenges in developing inertial fusion energy as a primary energy source are immense:

- Demonstrating the physics feasibility (this will be hopefully demonstrated on the NIF in the next few years).
- Developing high-efficiency, high-repetition, high-energy, short-wavelength laser systems.
- Developing the required target fabrication, injection, tracking, and beam-pointing technology.
- Developing high-durability, long-life optical systems capable of surviving in extremely hostile environments.



Conceptual designs of inertial fusion power plants based on laser drivers have been developed over the last few decades [176]. The laser for one such design from LLNL (shown above) is based on diode-pumped glass.

- Developing the appropriate first wall and blanket materials.
- Developing high-efficiency heat exchange systems.

The challenges are many but the motivation and ingenuity of this nation's scientists and engineers have been tested and proven in the past, and they will no doubt rise to the challenge if that challenge is presented to them. For its part, the University of Rochester's Laboratory for Energetics can be expected to be a key player in the development of this important technology.

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