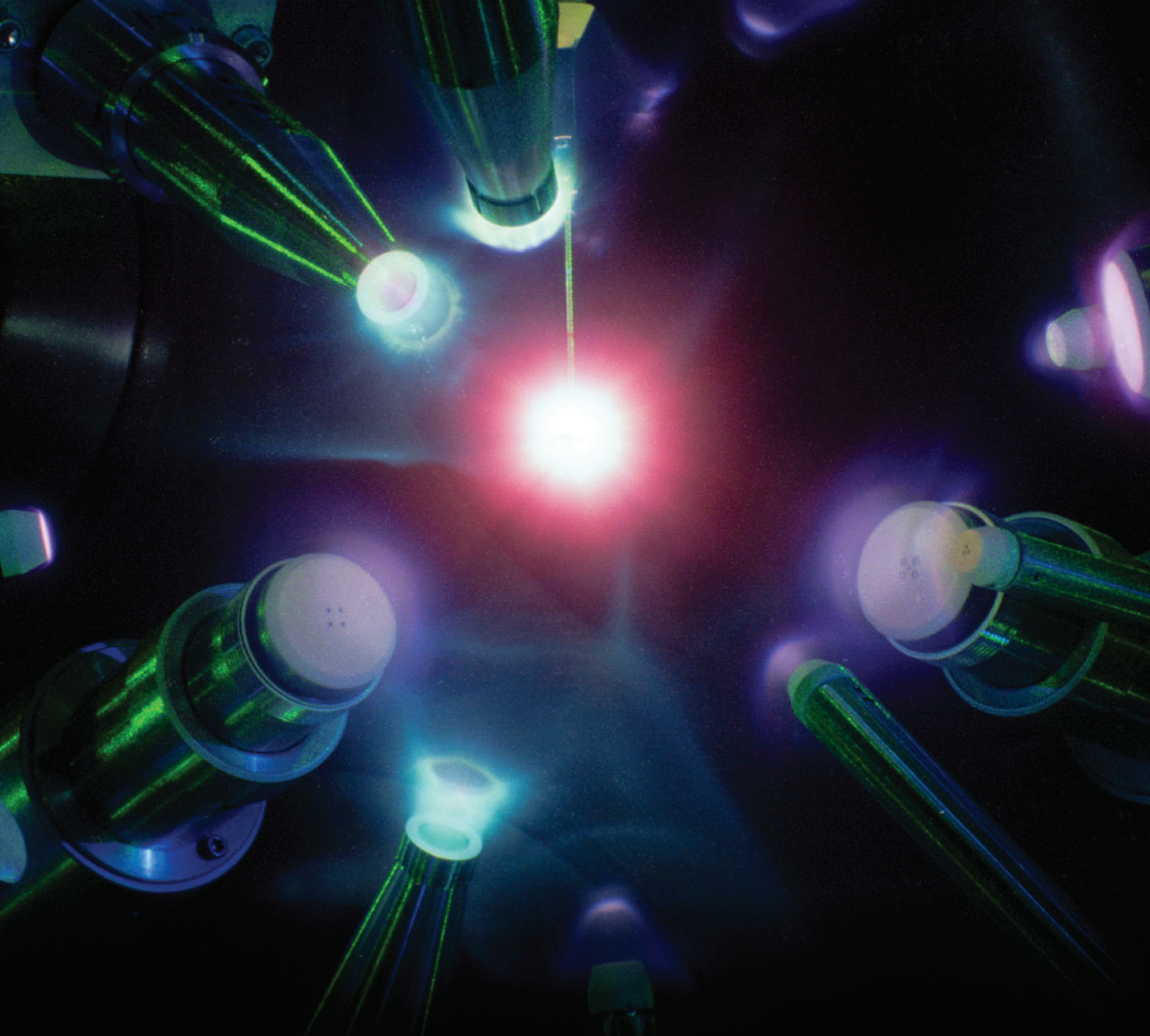

Inertial Confinement Fusion

An Introduction

The ENERGY of the STARS

Inertial Confinement Fusion: An Introduction

The ENERGY of the STARS

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Foreword

The University of Rochester's Laboratory for Laser Energetics (LLE) is a unique national resource for research and education in science and technology and a major asset of the University. 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 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. The LLE program has been jointly supported by the federal government, state government, industry, utilities, and a university.

Thermonuclear fusion is the process by which nuclei of low atomic weight such as hydrogen combine to form nuclei of higher atomic weight such as helium. Two isotopes of hydrogen, deuterium (composed of a hydrogen nucleus that contains one neutron and one proton) and tritium (a hydrogen nucleus containing two neutrons and one proton), provide the most energetically favorable fusion reactants. In the fusion process, some of the mass of the original nuclei is lost and 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.

Fusion is the process that gives thermonuclear weapons their awesome power. 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 existing nuclear *fission* reactors currently in use. The fuel for fusion, which occurs naturally in seawater, is essentially inexhaustible. To initiate fusion reactions, the fuel must be heated to tens of millions of degrees.

Two approaches are being investigated to demonstrate controlled fusion—magnetic confinement fusion and inertial confinement fusion. Inertial confinement fusion involves the heating and compression of fusion fuel by the action of intense laser or particle beams, where a small spherical target containing fusion fuel is subjected to intense irradiation by high-power sources that implode the target and compress the fuel while heating it to thermonuclear temperatures. When the fusion fuel has been compressed and heated to fusion conditions, "ignition" is possible. Ignition is the process whereby a self-sustaining propagating fusion reaction (thermonuclear burn wave) can occur and produce more energy than was used to bring the target to fusion conditions. The achievement of fusion ignition is a national grand challenge.

A demonstration of ignition in the laboratory is a prerequisite to the commercial production of electricity using thermonuclear fusion.

This small volume has been written so that readers of all backgrounds can learn and share the excitement of inertial fusion research. The author, Lois Gresh, has written 19 books that have made science come alive to audiences, both young and old. She is uniquely qualified to help you, the reader, learn about the science that has challenged mankind for over seven decades.

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Chapter 1

Overview

University of Rochester's Laboratory for Laser Energetics (LLE)

The University of Rochester's Laboratory for Laser Energetics (LLE) is the only inertial confinement fusion (ICF) research laboratory of its type at a U.S. university. We were established in 1970 and are supported by the U.S. Department of Energy, the New York State Energy Research and Development Authority, and the University. ***LLE is one of the most prominent inertial confinement fusion (ICF) centers in the world.***

The bulk of our current work focuses on inertial confinement fusion, which is the topic of this book. From both experimental and theoretical perspectives, we support the missions of the National Nuclear Security Administration's (NNSA) National Ignition Facility (NIF) at the Department of Energy. In short, our main focus is on the interaction of intense laser radiation with matter.

Figure 1.1: A view of the OMEGA EP laser, the newest ultrafast high-power laser facility, completed in 2008.

While this book focuses on ICF—what it means, how it works, why research into inertial confinement fusion is so important—a second, more advanced book explains other research topics at LLE.* Overall, the key activities at LLE are:

- Conducting experiments to support the National ICF Program.

- Operating the OMEGA and OMEGA EP lasers for the above experiments, as well as for other ICF laboratories (Lawrence Livermore National Laboratory, Los Alamos National Laboratory, Sandia National Laboratory, and the National Laser Users' Facility for academic users). The OMEGA laser stands 10 meters tall and is approximately 100 meters in length. This system delivers pulses of laser energy to targets in order to measure the resulting nuclear, plasma, and fluid dynamic events. OMEGA's 60 laser beams focus laser energy with a duration of approximately one billionth of a second onto a target that measures less than 1 millimeter in diameter. OMEGA EP couples short-pulse beams to the OMEGA laser and, as well, has a stand-alone experimental chamber. Its first target test shot was conducted in February 2008. It is the world's most energetic short-pulse laser.

- Developing advanced technologies. This includes a variety of programs supporting the main program above and includes optical materials, optical fabrication, diffractive optics, and laser development.

* As of March 2008, the advanced book is in progress and will cover both advanced technology development and high-energy-density physics.

- Conducting research and development related to high-energy-density physics (HEDP). Several efforts include astrophysics, magneto-inertial fusion equation of state of matter under extreme pressure, fast ignition, and ultrahigh-intensity laser interaction with matter.

- Providing graduate and undergraduate education in electro-optics, high-power lasers, plasma physics, and nuclear fusion technology.

Currently, LLE employs and provides research opportunities for nearly 500 staff, faculty, and students. Since 1989, LLE has been conducting a summer high school program; it is the only university-sponsored laser laboratory research program for high school students in the country. Between 2003 and 2008, the program produced two finalists for the prestigious Intel Science Talent award, as well as fourteen additional semifinalists.

The rest of this booklet teaches you the basics about inertial confinement fusion research at the University of Rochester's Laboratory for Laser Energetics. You'll learn how inertial confinement fusion works from the ground up, and then move to more complex topics. If you're anxious to learn about the history of lasers and inertial confinement fusion at LLE and how we envision the future, you might want to skip ahead to Chapter 4.

Inertial Confinement Fusion (ICF)

The term inertial confinement fusion may sound intimidating and highly technical at first, but the basic concepts are actually fairly simple. If you step through the process of inertial confinement fusion bit by bit, everything will become clear very quickly. In fact, that's what **Chapter 2, Nuclear Fusion 101**, is all about. For now, it suffices to understand the absolute basics, which relies on your junior high school knowledge of chemistry.

First, you probably recall that an atom is composed of positively charged protons and neutrally charged neutrons in its nucleus, and of negatively charged electrons that are outside the nucleus. The hydrogen (H) atom, in particular, consists of one proton and one electron, but there are other forms of H atoms called *hydrogen isotopes*. One is called *deuterium* (D), with one proton and one neutron. Another is *tritium* (T), with one proton and two neutrons.

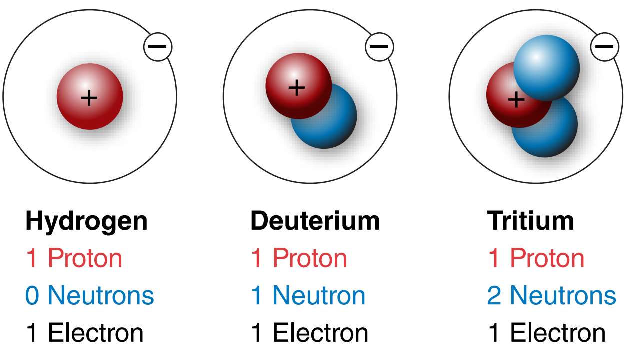


Figure 1.2: The composition of hydrogen and two of its isotopes—deuterium and tritium.

An element's *atomic mass* is basically the average mass of protons plus neutrons in its various isotopes. For example, hydrogen's average atomic mass is 1.0794 atomic mass units (amu) rather than 1.0073 amu (the atomic mass of the proton)

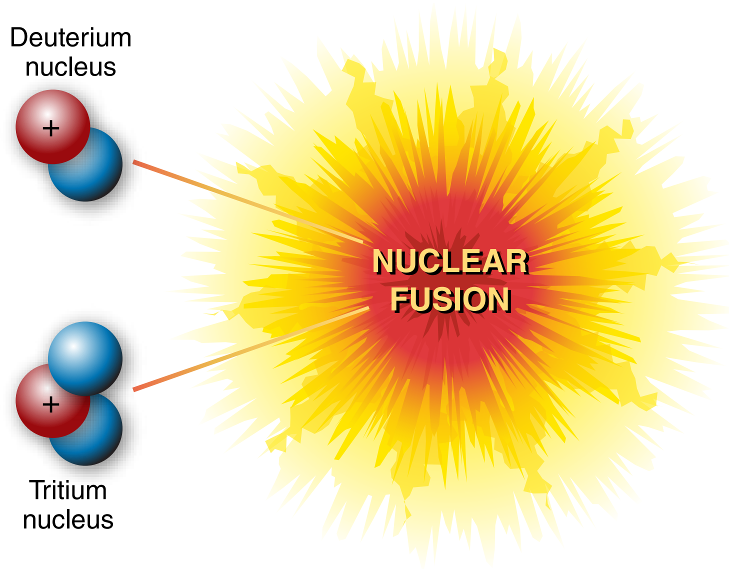


Figure 1.3: Nuclear fusion is the process by which multiple atomic particles join together to form a heavier nucleus.

because it has isotopes with neutrons (neutron atomic mass = 1.0087 amu). All of hydrogen's isotopes, including deuterium and tritium, have very low masses.

When nuclei of D and T collide and combine, an enormous amount of energy is released. When two particles collide and combine, it's called *fusion*. And because we're smashing nuclei together, the process is called *nuclear fusion*.

Nuclear fusion converts mass into energy per Einstein's famous $E = mc^2$ formula. It requires that we heat atoms to extremely high temperatures; in fact, to temperatures that break up the atoms into a gas of electrons and nuclei into what is called a *plasma*, which is the fourth state of matter (the other three are gas, liquid, and solid). The plasma must be *confined*—that is, contained and held together—heated to high temperatures, and subjected to high pressure for a long enough time to fuse more and more nuclei together. As more fusion reactions occur, more energy is released. This general process is known as nuclear fusion. There are several forms of nuclear fusion. In this book, we'll be discussing primarily inertial confinement fusion—ICF, for short.

Scientists expect that a nuclear fusion power plant will be able to generate 1,000 megawatts of electricity, enough to service 1,000,000 homes. A megawatt is a million watts, which is enough power to handle 1,000 homes or turn on 10,000 100-watt light bulbs. Nuclear fusion is basically an inexhaustible supply of energy. We will never run out of it. In addition, nuclear fusion does not release carbon dioxide and other pollutants into our atmosphere. It does not rely on oil or gas. It does not contribute to global warming.

Inertial confinement fusion gives us the energy of the sun and the stars—literally.

The energy of the stars is the ultimate energy of the universe. The sun is an average-sized star, and since the early 1900s, scientists have known that the sun produces its energy using nuclear fusion.

The Big Bang that created the universe itself resulted in nuclear fusion reactions. According to the "Big Bang Nucleosynthesis" theory, nuclear fusion began with hydrogen, and during the first three minutes of the expansion of the universe, deuterium, helium, and lithium were generated.

After the Big Bang, the fusion process settled down—after approximately a few hundred thousand years—and the hydrogen and helium in the universe cooled and formed huge gas clouds. A few hundred million years after the Big Bang, the gas clouds were compressed into stars.

As gas is compressed, it becomes hotter, so as the stars became compressed, their cores became very hot. In fact, the cores were millions of degrees hot, and nuclear fusion then began in the stars.

Stars today continue to use hydrogen and helium as fuel. Because the density of stars is so high, nuclear fusion occurs at a very fast rate. The sun and stars are natural fusion reactors.

On Earth, for many years, nuclear explosions were the only way to release large amounts of fusion energy. The invention of the laser in 1960 raised the possibility that fusion conditions could be created by laser heating and the compression of matter. Starting in the late 1960s, several laboratories around the world began springing up to replicate on Earth what happens in the stars.

These laboratories employ high-energy lasers to create nuclear fusion energy. One such laser was the Nova laser at the University of California's Lawrence Livermore National Laboratory (LLNL). Another is the OMEGA laser at the University of Rochester's Laboratory for Laser Energetics.

Highlights of this Chapter:

LLE is one of the most prominent nuclear fusion centers in the world.

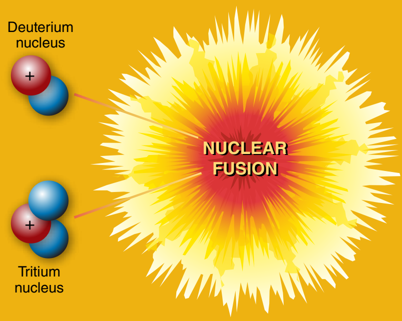
LLE conducts experiments to support the National Inertial Confinement Fusion (ICF) Program.

LLE develops many advanced technologies and also conducts research and development related to high-energy-density physics.

LLE provides graduate and undergraduate education in electro-optics, high-power lasers, plasma physics, and nuclear fusion technology.

Nuclear fusion is an affordable, plentiful, efficient source of energy.

Nuclear fusion gives us the energy of the sun and the stars—literally.



CHAPTER 2
NUCLEAR FUSION 101

Nuclear fusion is the process whereby light nuclei combine to form heavier ones—for example, when two hydrogen isotopes fuse together and form one atom of helium. We touched on this process in Chapter 1 to give you a rudimentary understanding of nuclear fusion. Now we'll delve more deeply into the topic.

Einstein's Famous Equation

We've all seen the equation $\mathbf{E = mc^2}$. But what does it mean? And what does it have to do with nuclear fusion?

Let's start at the beginning. Energy, or **E** in the equation, refers to the general concept of work, or **w**. When a force, denoted by **f**, moves an object through a distance, denoted by **d**, then the work produced is equal to force times distance. Simply put, we have:

$$\mathbf{w = f \times d}$$
Work = Force × Distance

The force must be applied in the same direction as the movement of the object.

Energy **E** is related to work **w**. By releasing energy, we are able to do work. By doing work, we supply energy to what we are working on.

In actuality, energy and work are equivalent:

$$\mathbf{E = w = f \times d}$$
Energy = Work = Force × Distance

In the metric system, one unit of energy is called a *joule*. It's also called a *newton-meter*. One joule exerts a force of one newton for a distance of one meter. (A newton is a measure of force. In fact, one newton is the force required to accelerate a 1-kilogram mass from rest to a speed of 1 m/sec in one second.)

The energy of an object in motion is its *kinetic energy* **KE**, where

$$\mathbf{KE = 1/2\ (mv^2)}$$
Kinetic Energy = 1/2 [mass × (velocity of the object)^2]

By now, you're probably noticing what we're hinting at, that mass and velocity and energy and force and distance are all related. This is a highly logical and obvious conclusion. When you open a door, you push on it, exerting pressure or force. But how far the door opens also depends on other things, such as the mass of the door and the direction in which you're pushing it.

In fact, energy and mass are more than related. In our universe:

Energy is Conserved
Mass is Conserved

Energy is Equivalent to Mass

We can convert energy from one form to another—from heat to light to motion—without losing any of the energy. The total energy remains the same. Similarly, we can convert mass from one form to another without losing any of the total mass. It was Albert Einstein, in 1905, who first proposed that energy and mass are equivalent.

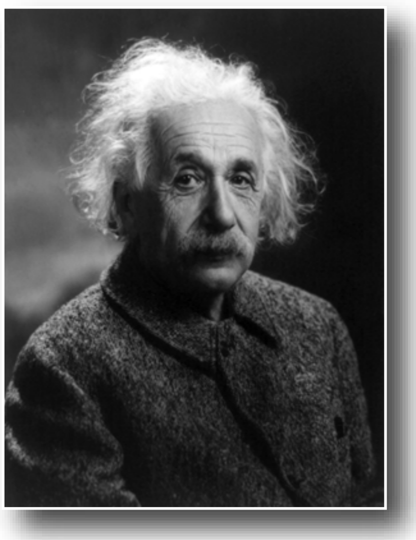


Figure 2.1: Albert Einstein (1879–1955) is best known for his theory of relativity and specifically for the concept that mass and energy are equivalent.

Using the laws of momentum and conservation of energy, Einstein showed that, if an object supplies energy **E** in the form of radiation, then the object's mass is reduced by $\mathbf{E/c^2}$. Hence, $\mathbf{m = E/c^2}$. And using simple algebra:

$$\mathbf{E = mc^2}$$

Energy equals mass times the velocity of light squared

Velocity of Light

The velocity of light is always shown by the letter **c**. The **c** stands for the word constant. It also stands for the Latin word *celeritas*, which means swiftness. The velocity or speed of light refers to all electromagnetic radiation, including visible light, traveling in a vacuum. It is exactly 299,792,458 meters per second (approximately 3×10^8 meters per second). It is 186,282.397 miles per second.

When traveling through air or glass, light slows down compared to its speed in a vacuum. The ratio of **c** to the slower speed is known as the refractive index of the air or glass.

Once scientists realized that mass and energy are equivalent, they began speculating about whether it was possible to tap the power unleashed by the sun and stars. As more was learned about energy, temperatures, elements, and atoms, scientists began to formulate ways to use nuclear fusion to create unlimited amounts of energy on Earth.

From Elements and Atoms to Isotopes and Ions

Heat is a form of kinetic energy of the atoms and molecules in matter. The average kinetic energy of an object is directly related to the object's temperature.

Temperature is measured in degrees Celsius, also called centigrade (°C). It is also measured in degrees Fahrenheit (°F) and in kelvins (K).

Absolute zero is defined as zero K, where molecular motion ceases and no known system can transfer heat. Temperatures do not drop beneath zero K on the kelvin scale. Water freezes at 273.15 K, or 0°C. Water boils at 373.15 K, or 100°C. One degree on the K scale equals 1°C.

The temperature of the sun is 14 million K, or 14 million degrees Celsius.

To give you a clue about where we're going with this discussion, one milligram of hydrogen at a temperature of 10 million degrees Celsius confined within one

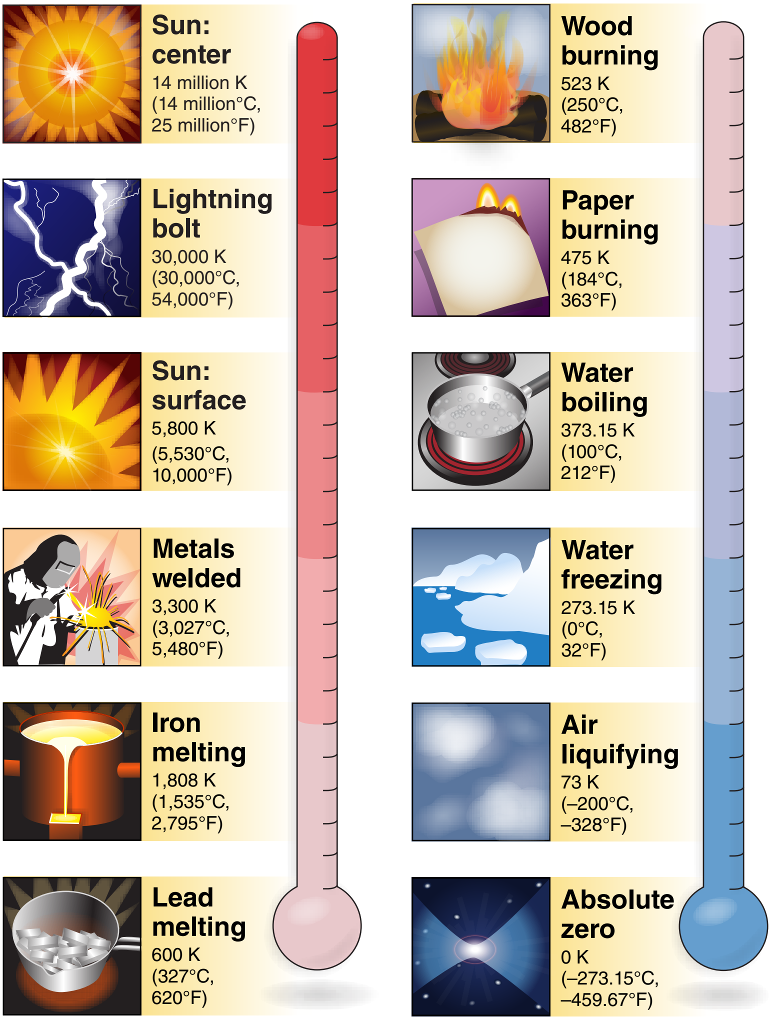


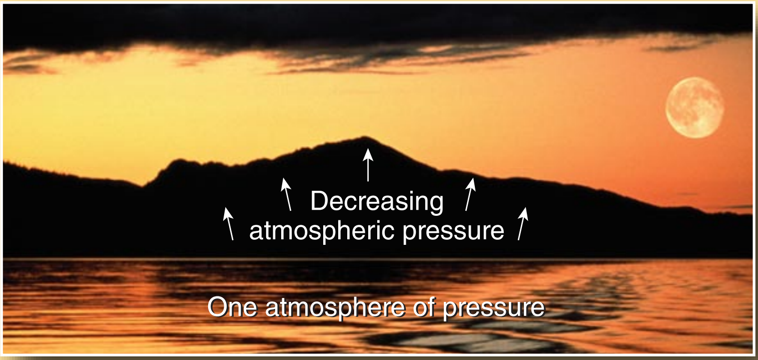
Figure 2.2: A large range of temperatures is encountered in nature.

cubic centimeter is equivalent to a pressure of one megabar (often written as Mbar), which equals one million—10^6—atmospheres.

This is a huge pressure. Considering that one atmosphere (1 bar) is the pressure of the air over the surface of a sea, imagine how much force is applied by 10^6 atmospheres!

The main point to remember right now is that it requires an enormous amount of pressure to confine hydrogen that is heated to approximately the temperature of the sun (or a star). Pressure and energy density are equivalent. And in actuality, we heat the fuel of nuclear fusion to a much higher temperature—to approximately 100 million degrees Celsius.

One Atmosphere
One **atmosphere** of pressure is equal to 101,325 pascals. For the mathematically inclined, one pascal is equal to one newton per square meter. It corresponds to an energy density of one joule per cubic meter. For the less mathematically inclined, we can think of an atmosphere as the force exerted by the air above the surface of the earth. Standard sea-level pressure equals one atmosphere.



Keeping in mind everything you just learned about energy, mass, temperature, and pressure, let's return briefly to elementary chemistry. Then we'll tie everything together.

Deuterium and Tritium

As far back as 1920, Arthur Eddington proposed that energy is liberated from stars when hydrogen combines to form helium. He drew this conclusion from Francis Aston's discovery that when four hydrogen atoms form helium, the sum of the masses of the four hydrogen atoms exceeds the resulting mass of the helium atom. Because mass and energy are interchangeable, the loss in mass implied an increase in energy.

In fact, Eddington even guessed that the combination of hydrogen to form helium could very well be the process used by the sun and stars to produce energy.

Then along came quantum mechanics, which, among other things, showed that nuclear fusion can occur at temperatures similar to those found in the sun. The main recipe is shown in the following graphic.

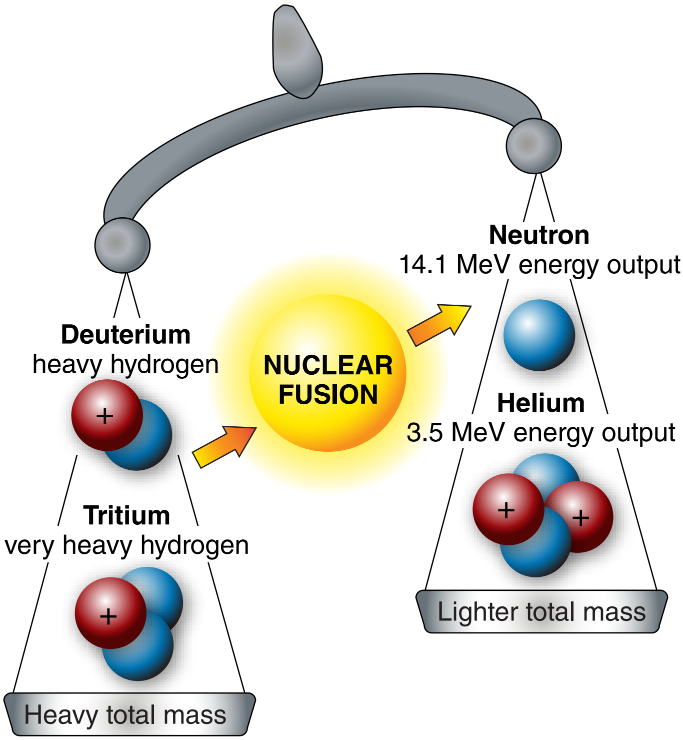


Figure 2.3: Nuclear fusion of light nuclei results in the production of a heavier nucleus but lower total mass. The mass difference results in a nuclear fusion energy release.

As you can see, when you combine D and T to form helium, a neutron is also released, as well as 17.6 MeV of energy. An electron volt, eV, is an energy unit for atoms. It is equal to 1.6×10^{-19} joules. An MeV is equal to 1 million electron volts. Actually, 17.6 MeV isn't an enormous amount of energy.

Energy Equivalence

Given:

3,600 joules = 1 watt-hour

1 kilowatt-hour = 1,000 watt-hours

Household electricity is measured in kilowatt-hours.

An average household requires 20 kilowatt-hours per day.

How many joules does it take to run a household for one day? A week? A month?

Answer:

20 kilowatt-hours = 20,000 watt-hours × 3,600 joules/watt-hour
= **72,000,000 joules/day**

72,000,000 joules/day × 7 days/week
= 504,000,000 **joules/week**

504,000,000 joules/week × 4.3 weeks/month
= 2,167,200,000 **joules/month**

To really make this work and supply energy for people to use would require that we combine a lot of deuterium and tritium. Luckily, deuterium is available in ordinary water. Tritium is a little harder to obtain, however, and requires that we combine the fusion neutron with an abundant light metal called lithium.

The final ingredient is temperature—a very high temperature of 100 million degrees Celsius, approximately ten times the temperature in the center of the sun.

The deuterium and tritium must be confined so they can fuse together and produce the initial burst of energy. In outer space, the sun and stars confine the ions through gravity. Here on Earth, at the Laboratory for Laser Energetics, we use *inertial confinement fusion*. This is the subject of **Chapter 3, Nuclear Fusion 201.**

Highlights of this Chapter:

Mass is equivalent to energy.

Heat is a form of kinetic energy of the atoms and molecules in matter.

Deuterium is in ordinary water.

Tritium is obtained from fusion neutrons combined with lithium.

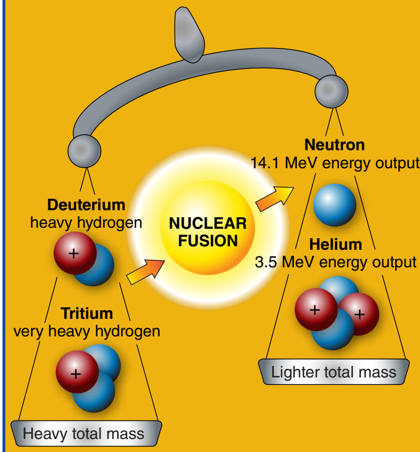
100 million degrees Celsius is needed for the fusion process.

Combining deuterium and tritium at very high pressures and temperatures yields fusion energy.

Pressure and energy density are equivalent.

Inertial confinement fusion keeps the ions together long enough to fuse and produce a burst of energy.

Nuclear fusion gives us the energy of the sun and the stars—literally.



Chapter 3
Nuclear Fusion 201

This chapter will complete your basic education about nuclear fusion. You already know the basics from **Chapter 2, Nuclear Fusion 101**. Now, we'll build on what you've learned and tell you how the energy of the sun and stars is produced right here on Earth at the University of Rochester's Laboratory for Laser Energetics (LLE).

Inertial Confinement Fusion: The Basics

Remember from the last chapter that pressure and energy density are equivalent. The sun's central pressure is approximately 3.5×10^{11} atmospheres, which is the same as 3.5×10^{5} megabars, or 350 gigabars. The core pressure of a typical star is approximately 10^{11} to 10^{12} atmospheres.

A typical star's pressure is about 1 trillion atmospheres.

Until recently, this type of pressure and the subsequent release of star-like fusion energy could only be produced on Earth through nuclear explosions. With inertial confinement fusion, the Laboratory for Laser Energetics is able to produce these kinds of temperatures and pressures in the laboratory. A laboratory such as LLE is one of the few places on Earth where we can create conditions that can be achieved only in stars and nuclear weapons, yet live to tell about it.

Basically what happens in inertial confinement fusion is that lasers or particle beams are used to compress and heat a small mass of fusion fuel, which then undergoes nuclear fusion and burns. Energy is applied to the outside of a spherical capsule that contains heavy hydrogen fusion fuel. The energy causes the capsule to ablate outward much like the exhaust of a rocket engine. This "ablation" creates a reaction force on the inner portion of the capsule, causing it to implode. The implosion compresses and heats the interior fuel, which undergoes fusion and releases energy. The implosion stops when the pressure at the core of the capsule becomes sufficiently high. The remaining fuel then expands outward and cools, and the fusion reactions cease.

According to Isaac Newton's First Law of Motion, in an isolated (or confined) system, an object will remain at rest and an object moving with constant velocity will continue at that velocity unless an outside force intervenes. So in inertial confinement fusion, the inertia of the fuel keeps it from escaping from the core, enabling it to continue burning and producing energy until its pressure is high enough to stop the implosion.

You might recall from Chapter 2 that each D–T fusion reaction releases 17.6 MeV of energy. To produce a lot of energy, inertial confinement fusion aims to produce approximately 10^{20} D–T reactions for each shot from a laser. Moreover, the goal is to shoot several DT targets per second. The D–T reaction is the central focus of worldwide fusion research, a choice dominated by the fact that it is the easiest fusion reaction to initiate.

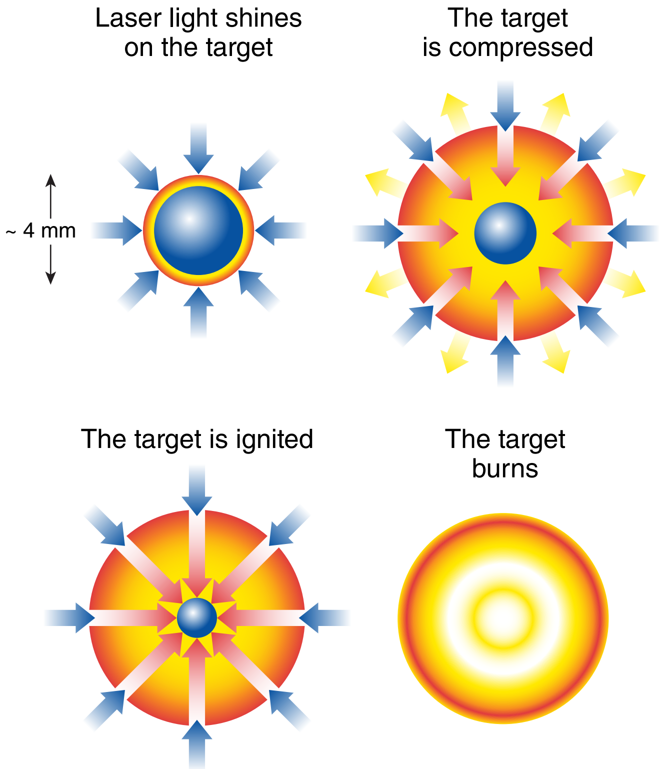


Figure 3.1: Inertial fusion uses laser or particle beam energy to implode a small fuel-containing target, which then undergoes nuclear fusion and burns.

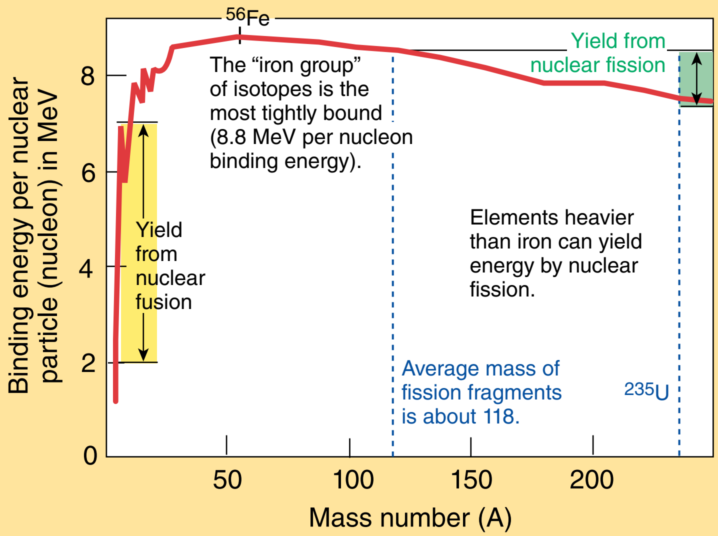
The Binding Energy Curve

The *nuclear binding energy* holds the nucleus together and is the difference between the mass of the nucleus and the sums of the masses of the protons and neutrons. The mass of the nucleus is always the smaller of the two values.

Remember: deuterium consists of a neutron and a proton. When deuterium is formed, approximately 2 MeV is released, and the neutron and proton are bound together. To break deuterium apart into its constituent neutron and proton requires the input of 2 MeV.

When two deuteriums combine, they form a helium nucleus. The nuclear binding energy of helium is approximately 7 MeV.

You can see these values on the *Binding Energy Curve* (red) below.



Just as helium is made from two deuteriums, heavier and heavier elements continue to form, but as you can see from the Binding Energy Curve, iron (Fe), which is the most tightly bound, forms at an energy of approximately 8.8 MeV per nucleon.

The heavier an element, the more electric charge it has. While the protons repel each other, the strong nuclear force attracts them together.

The total energy is the binding energy from the strong nuclear force minus the repulsion force from the electric charge.

After Fe, the repulsion force begins to get strong enough to reduce the binding of the protons. The binding energy per nucleus begins to drop. The atomic mass of Fe is 56, and the binding energy plateaus at ~8.8 MeV per nucleon for atomic masses up to approximately 118. Then the binding energy begins to drop. You can see this clearly in the Binding Energy Curve (see p. 19).

Notice also that uranium (U), with an atomic mass of 235, has a nuclear binding energy of approximately 7.3 MeV per nucleon. When U breaks up during nuclear fission, it produces two nuclei, each with an atomic mass of approximately 118. So we produce energy from *nuclear fusion* when we move up the left side of the red curve, and we produce energy from *nuclear fission* when we move from right to left from U-235 back to 118 on the red curve.

A regular star stops at Fe and never moves past the plateau that you see in the Binding Energy Curve. The star runs out of fuel and stops burning. U-235 is actually created during supernova explosions.

For every 6,500 atoms of hydrogen in seawater, there is one atom of deuterium. Since each D–T fusion reaction produces one neutron, it is possible to breed tritium by surrounding the DT fuel with a lithium blanket where the reaction, **lithium + neutron yields tritium + helium**, takes place.

Nuclear fusion of all the deuterium extracted from one cubic kilometer of seawater could generate the same energy as the combustion of the entire world's oil reserve.

"Development of an economically viable fusion reactor would literally give us the energy equivalent of oceans of oil. Because seawater contains about 40 grams of deuterium and 0.1 grams of lithium per tonne, every barrel of seawater contains the energy equivalent of almost 30 barrels of oil in deuterium fuel and about one-fifth of a barrel of oil in D-T fuel (where tritium is obtained from neutron reactions on lithium). A volume of seawater equal to the top meter of the earth's oceans would yield enough fuel to supply D-T fusion reactors for thousands of years of electricity production at today's rate of usage."

[J. D. Lindl, R. L. McCrory, and E. M. Campbell, "Progress Toward Ignition and Burn Propagation in Inertial Confinement Fusion," Phys. Today, **45** (9), 32–40 (1992).]

The typical mass of one DT capsule used in laser-fusion experiments is just a few milligrams, and it can yield hundreds of megajoules of fusion energy. Since 150 megajoules is the energy released by the combustion of one gallon of gasoline, a fusion energy yield of hundreds of megajoules from a few milligrams of DT fuel is clearly a manageable energy output.

Inertial Confinement Fusion: The General Process

There are two basic approaches to inertial confinement fusion. One is called the direct-drive method, and the other is the indirect-drive method. We'll talk about the indirect-drive method a bit later.

The world's leading center for direct-drive fusion is at the University of Rochester's Laboratory for Laser Energetics (LLE). The leading center for indirect-drive fusion is at the Lawrence Livermore National Laboratory (LLNL) in California.

Direct-Drive Approach

The *direct-drive* approach involves shooting laser light directly on a spherical capsule. A *laser* adds energy to atoms in a substance known as the *lasing medium*. (A more sophisticated definition is that a laser is a light amplifier system that is based on an optical excitation of atoms in a lasing medium.) One example of a lasing medium is a ruby crystal. At LLE, the OMEGA laser uses neodymium (Nd)-doped glass, which generates light with a wavelength of one micron—in the infrared.

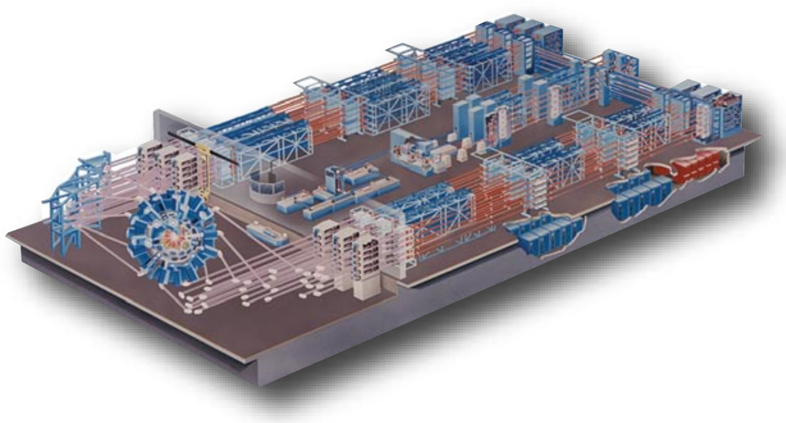
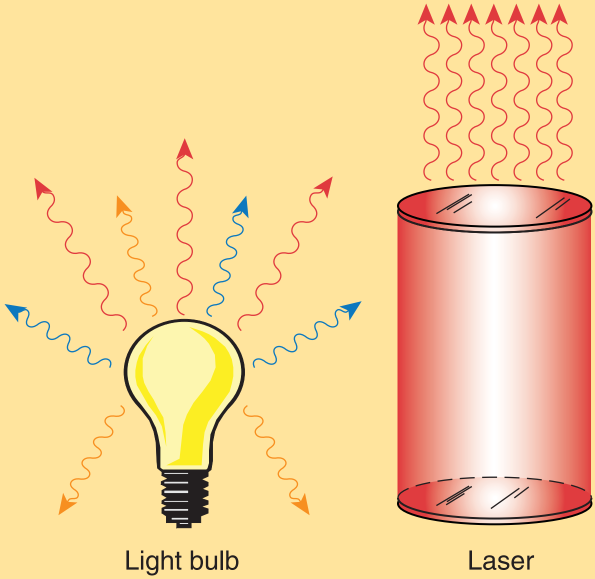


Figure 3.2: Artist's rendering of the OMEGA laser at LLE. The OMEGA laser produces peak powers in excess of 30 times the peak electric power production of the United States—at an instant in time.

Lasers

An intense light source (xenon-filled flash lamp) bumps atoms to higher energy levels in the lasing medium. Some of these excited atoms emit photons, which in turn, cause other excited atoms to emit photons. As the process continues with a cascade of emitted photons, the laser generates an intense, narrow beam of light that has a specific frequency. Because the generation of the intense beam of light is stimulated by this cascade of photons, the process is known as *stimulated emission*. The word *laser* is actually an acronym for "light amplification by stimulated emission of radiation."

Put another way, a laser basically stores energy and extracts it quickly as *coherent light*, which means all the photons are emitted in a narrow beam rather than being scattered in all directions. By contrast, an incandescent light bulb generates *incoherent light*, in which photons are emitted in all directions at a wide variety of wavelengths.



In its simplest form, the capsule (*target*) would be just a bubble of deuterium and tritium, which has been solidified into a shell. Current LLE experiments, however, actually have a thin plastic shell (balloon) only a few microns thick that is filled with deuterium and tritium. The capsule is *cryogenic*, in that deuterium and tritium are frozen on the inside of the shell, with the frozen surface about 100 microns thick and the plastic approximately 5 microns thick.

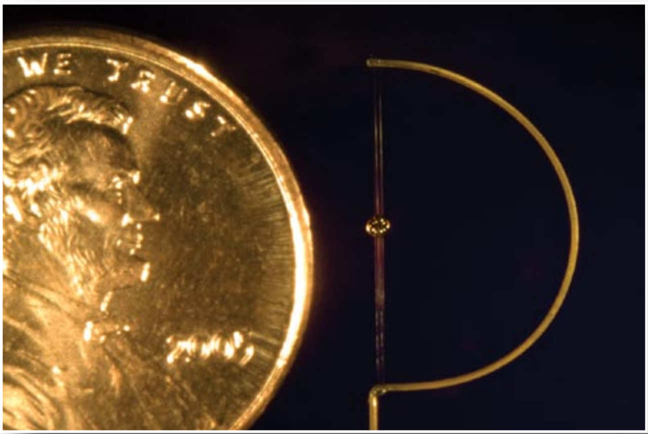


Figure 3.3: The laser-fusion targets used on OMEGA experiments are typically ~1 mm in diameter and are suspended by spider silks.

The target itself is suspended by filaments, often made of spider webbing, attached to a positioning device.

When the laser irradiates the target, it immediately starts to remove, or *ablate*, the material from the surface. The laser burns through the plastic and begins ablating the heavy hydrogen that forms the bulk of the shell.

According to Newton's Law, that for every action there is an equal and opposite reaction, this process creates a reaction force that is directed inward, or toward the center of the target. Any shell material that is not ablated also rushes inward. The surface of the capsule absorbs the light from the laser, creating a very high temperature ionized gas (plasma).

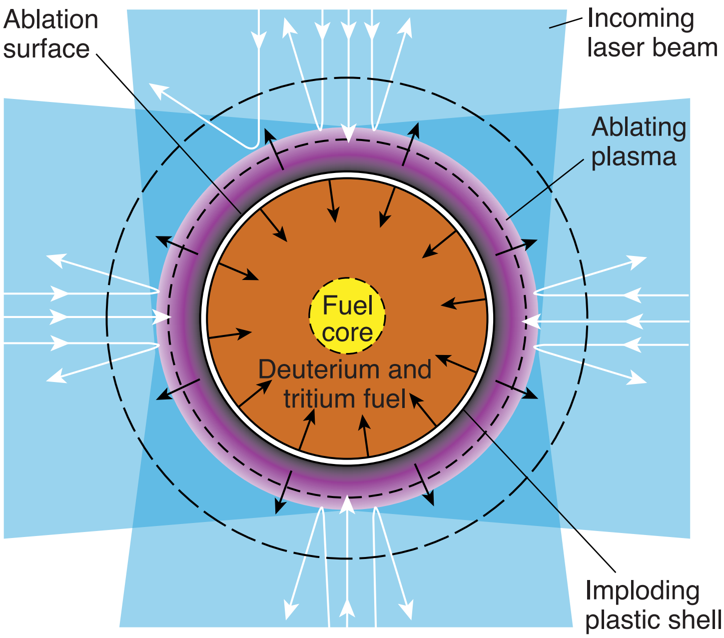


Figure 3.4: A laser-fusion target is compressed by reaction to the ablating plasma flowing away from the target.

Plasma

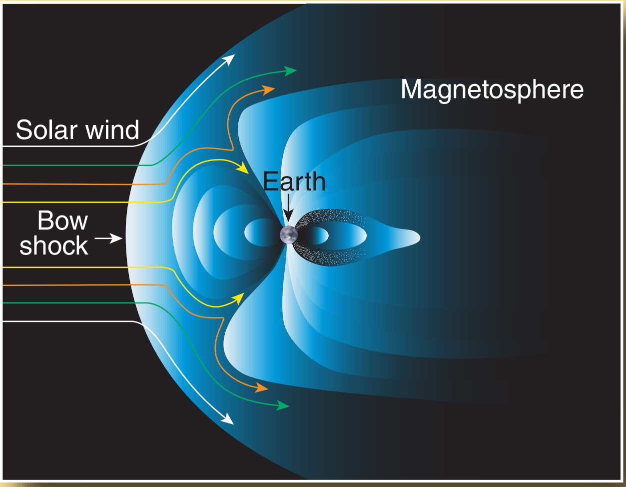
To create the fusion of the stars here on Earth, we must heat atoms to extremely high temperatures. When electrons are removed from neutral atoms at high temperatures, plasmas form.

A *plasma* is an ionized gas made up of positively and negatively charged particles, and as such, plasma interacts very strongly with electric and magnetic fields.

The word plasma first came into use in 1929, when Tonks and Langmuir wrote, "…when the electrons oscillate, the positive ions behave like a rigid jelly…" [L. Tonks and I. Langmuir, "Oscillations in Ionized Gases," Phys. Rev. **33**, 195–209 (1929).]

By confining the plasma—that is, keeping it all together in one location for a long enough time under high temperatures—we are able to initiate fusion reactions.

Plasmas are common in our world and in the universe. On Earth, examples of plasmas are neon and fluorescent lights and lightning. In outer space, stars and nebulas consist of plasma, as does the sun. In addition, the sun emits powerful plasma streams, called the solar wind, at velocities up to 500 kilometers per second. Particles from the solar wind become trapped in Earth's magnetic field (magnetosphere) and form radiation belts.



Earth's magnetic field interacts with the particles from the solar wind and creates extraordinarily beautiful displays called the Aurora Borealis, or Northern Lights.

Figure 3.5: Sketch of the earth's magnetosphere (top) and a photograph of an Auroral display (bottom).

The process is like a rocket, only it's a spherical rocket in this case, and the material on the inside is pushed inward and compressed, eventually collapsing on itself. Much of the kinetic energy of motion is converted into thermal energy at very high temperatures and densities. This is also known as an *implosion*, a quick inward collapse of the target. At this point, the fusion reaction begins.

The main difficulty in triggering fusion reactions comes from the fact that the two reacting nuclei are both positively charged and repel each other due to electrostatic (coulomb) forces. Overcoming the coulomb forces can be accomplished only by literally "smashing" the two nuclei against each other. If the nuclei have a sufficient relative velocity (and therefore, relative kinetic energy) to overcome the coulomb barrier, a fusion reaction can occur. The relative kinetic energy can be provided to the reacting nuclei by heating them to very high temperatures. To trigger a large number of fusion reactions, the DT nuclei must be heated to temperatures of approximately 100 million degrees Celsius.

Heating the DT fuel to high temperatures is not the only requirement for igniting thermonuclear fuel. A laser-driven capsule expands rapidly after reaching the peak of compression. The capsule remains in the compressed state for less than a billionth of a second before expanding. During this time, enough fusion reactions must occur to produce sufficient useful energy.

Both the ignition of the fuel and the total number of fusion reactions depend on the compressed fuel density. Densities of several hundred grams per cubic centimeter are required to ignite and burn a significant fraction of the fuel. Since the fuel pressure is proportional to the product of density and temperature, hundreds of *gigabars* [where a gigabar is 10^9 (or one billion) atmospheres] are reached when ultrahigh dense material at hundreds of grams per cubic centimeter is heated to superhigh temperatures of hundreds of millions of degrees.

The density of a compressed capsule is more than twenty times that of the center of the earth. The density of the earth's core is about 15 grams per centimeter cubed. The density of a compressed capsule is about 200 to 300 grams per cubic centimeter. OMEGA experiments have already achieved densities of over 100 grams per cubic centimeter.

Sometimes, for various experiments to test our understanding of the implosion process, targets are used that are not frozen, but rather, are warm. These are plastic or glass shells filled with a few atmospheres of D and T gas. The reason LLE uses warm targets as well as cryogenic ones is that it's less expensive to use the warm targets for some of these experiments.

With a frozen target, compression to very high densities occurs much more efficiently because we're starting with a frozen solid, which has a much higher density than a warm gas. The initial compression doesn't require as much energy.

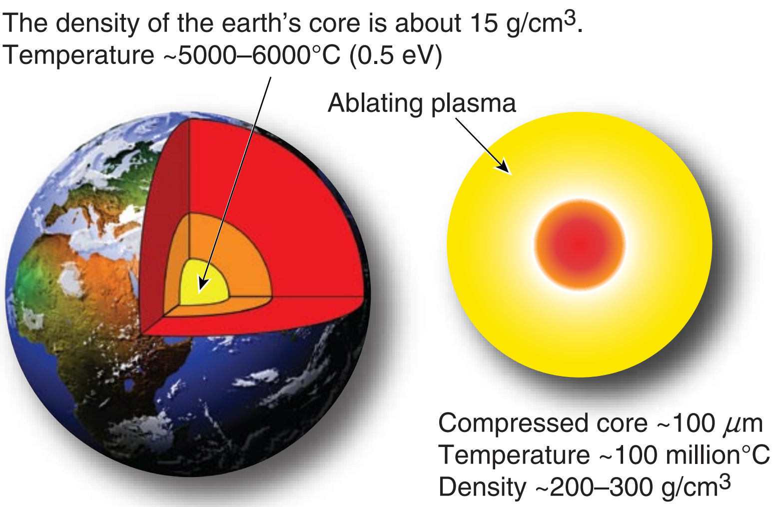


Figure 3.6: The density at the center of an imploded laser-fusion target is twenty times higher than the density at the center of the earth!

Indirect-Drive Approach

In the indirect-drive method, one starts with a spherical target that is inside a cylindrical enclosure called a *hohlraum*.

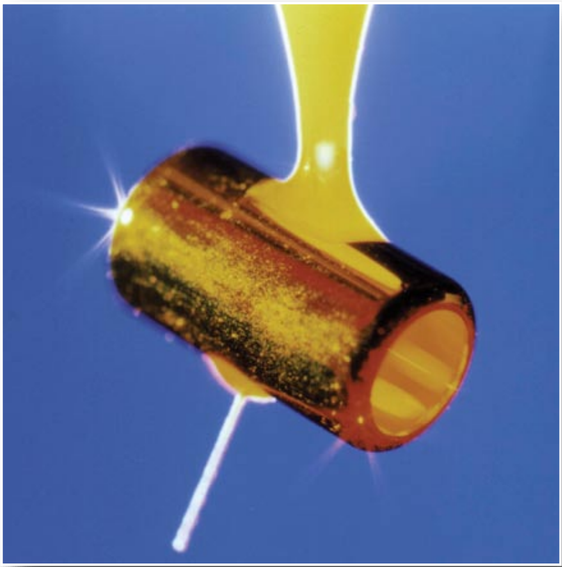


Figure 3.7: A typical indirect-drive target.

The cylinder is internally irradiated with laser light. Gold is typically used to create the hohlraum. Almost all of the laser light is absorbed by the gold, which emits x rays with very high efficiency. The fuel-containing capsule inside the hohlraum is generally made of low-atomic-weight materials such as plastic, beryllium, or even diamond.

The process of indirect drive is similar to direct drive in that both basically compress the fuel to very high densities and temperatures. But instead of shooting laser light directly at the target, as with direct-drive fusion, the indirect method generates x rays, which are then used on the target. The advantage of the indirect method is that it may provide more uniform irradiation of the target because the cylinders fill almost uniformly with the x rays.

Think of the inertial fusion target as a stress ball that you're trying to squeeze between your fingers. There will always be gaps where your fingers are not placed. The ball will squeeze outward at those gaps. Both the direct and indirect-drive approaches attempt to provide the most uniform possible irradiation conditions for the fusion capsule.

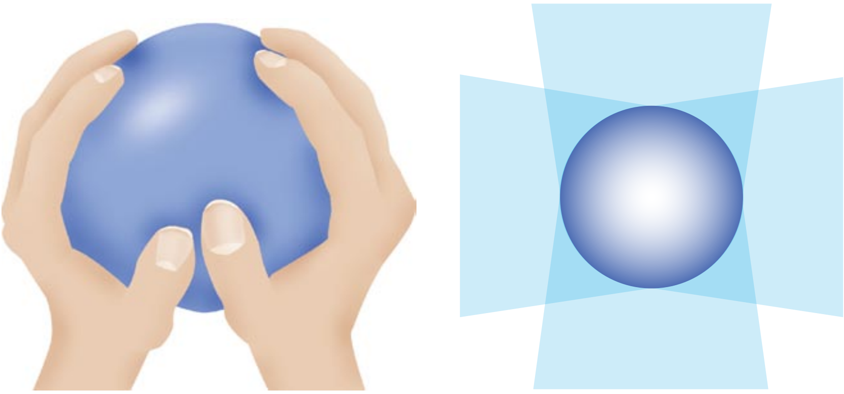


Figure 3.8: Just as a stress ball cannot be uniformly compressed by being squeezed between several fingers, a laser-fusion target can be uniformly compressed only by being irradiated with many overlapping laser beams.

A disadvantage of the indirect-drive method is that it is less efficient at generating energy. The hohlraum is a cylinder and inside the hohlraum is the actual target. With the indirect method, the target has holes in it through which the laser must pass. Most (but not all) of the laser's energy is absorbed by the inner walls of the hohlraum. A large fraction of this absorbed energy is radiated as x-ray energy, and some of this x-ray energy is deposited and absorbed by the fusion target. Therefore only a fraction of the laser's energy gets coupled to the actual target.

At the National Ignition Facility (NIF), for example, which uses indirect-drive inertial confinement fusion, actual energy coupling is expected to be approximately 15%. When the NIF was originally designed, it was believed by many in the inertial confinement fusion field that it would be almost impossible to put light on a spherical target uniformly enough to compress it to sufficiently high densities. That's why indirect-drive inertial confinement fusion was chosen as the basis of the NIF design. Both the direct and indirect-drive schemes are likely to work for energy production, and the method that is actually chosen will depend on the results of experiments in future years.

At the present time, the Laboratory for Laser Energetics (LLE) can handle both direct-drive and indirect-drive inertial confinement fusion. The current OMEGA Laser Facility shoots 60 beams at each target, and the configuration has been optimized for spherical targets since 1995. If LLE's direct-drive target designs were shot at the NIF, we expect that for a megajoule of laser light on the target, we would get 30 to 40 megajoules of fusion energy out.

Highlights of this Chapter:

Energy density of a typical star is 10^{11} to 10^{12} atmospheres.

The sun's central pressure is 3.5×10^{11} atmospheres.

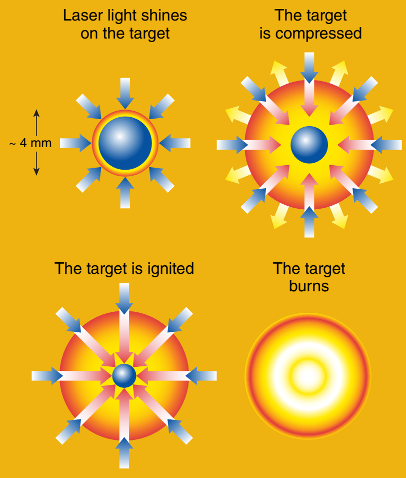
Energy density of an LLE target is 10 to 100 gigabars.

A few milligrams of DT fuel yields hundreds of megajoules of energy.

LLE conducts experiments with both direct-drive and indirect-drive fusion.

The world's leading center for direct-drive fusion is LLE.

Nuclear fusion gives us the energy of the sun and the stars—literally.



Chapter 4
Nuclear Fusion Honors Seminar

Now you can relax. All the hard work is behind you. If you've read the first three chapters, then you already understand what inertial confinement fusion is and why it could provide a plentiful, safe, and inexpensive source of endless energy. This chapter, **Nuclear Fusion Honors Seminar**, details some of the early history of LLE, gives you an in-depth look at how ICF research at LLE has progressed over the years, and lets you see where inertial confinement fusion is heading.

History of Nuclear Fusion at LLE

Why did the University of Rochester create the Laboratory for Laser Energetics? What was its original purpose, and how has it changed over the years? Obviously, the invention of the laser had something to do with the inception of LLE, and obviously, somewhere along the way, LLE realized that it would use lasers to create energy with nuclear fusion.

First let's look at a timeline that roughly shows the steps leading to the invention of the laser:

1900 Quantum physics is born. Max Planck coins the term *quanta*, which refers to the discrete bundles of energy related to matter.

1905 Albert Einstein shows that light is composed of packets that are later called *photons*. (Nobel Prize, 1921)

1913 Niels Bohr devises the model of the atom.

1917 Einstein realizes that light shining on an excited atom can force the atom to emit a photon. An emitted photon has the same frequency and direction as the photon in the light. This is called *stimulated emission*.

1951–53 Charles Townes uses stimulated emission to create a *maser*, "microwave amplification by stimulated emission of radiation." (Nobel Prize, 1964, shared with Basov and Prokhorov)

1958 Townes and Arthur Schawlow create the theory of stimulated emissions working at shorter wavelengths such as light. Birth of the term *laser*, "light amplification by stimulated emission of radiation."

1960 Theodore Maiman builds a laser with a synthetic ruby.

In 1960, Theodore Maiman built the first laser by shining a pulsed light on a ruby rod coated with silver on the ends. The pulsed light, which was a powerful flash lamp similar to what was used in high-speed photography, lasted a few milliseconds, just enough to excite the ruby. The laser released an intense pulse of light, which was one color (red) and coherent (as defined earlier, this means the emitted photons were generated in a narrow band and not scattered in different directions). His paper about the laser was published as: Th. Maiman, "Stimulated Optical Radiation in Ruby," Nature **187** (4736), 493–494 (1960).

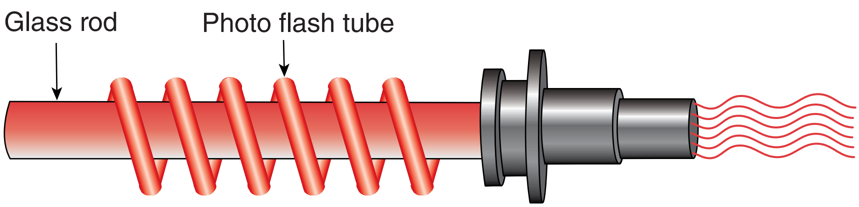


Figure 4.1: A solid-state laser absorbs light from a flash lamp and can produce a single-wavelength, collimated beam of light.

In 1961, University of Rochester scientist Mike Hersher started a synthetic ruby laser program at The Institute of Optics.

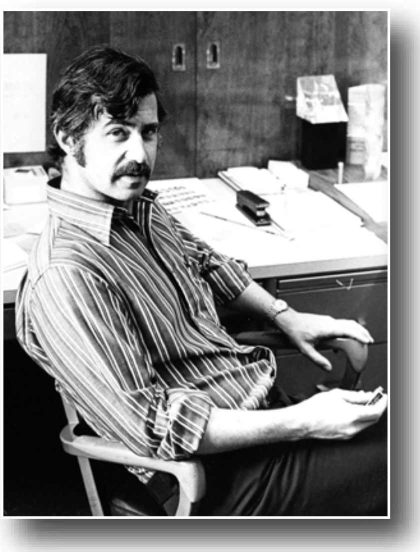


Figure 4.2: Mike Hersher investigated ruby lasers at The Institute of Optics starting in 1961—a year after the invention of the laser.

In 1965, Moshe Lubin joined the University of Rochester as a professor in what was then the Department of Mechanical and Aerospace Sciences (now the Mechanical Engineering Department). When he saw that Mike Hersher's ruby laser could be focused in air and create a huge spark, Lubin realized the laser approach was an ideal way to make and study plasma, as well as other high-energy-density phenomena. He started receiving funding from an eclectic group of sponsors and initiated numerous laser research projects.

Figure 4.3: Moshe Lubin was the founding director of LLE.

In 1970, the Laboratory for Laser Energetics (LLE) was formally established in the Gavett and Hopeman engineering buildings. The mission of the Laboratory was to investigate the interaction of intense radiation with matter. A handful of scientists was involved from the Department of Mechanical and Aerospace Sciences, as well as from the University of Rochester's Institute of Optics.

Figure 4.4: The LLE team in the early 1970s.

In 1972, Lubin had sufficient interest from the private sector to begin the Laser Fusion Feasibility Project (LFFP). The goal of the project was to demonstrate that laser fusion could be used for energy. With the strong support of Robert Sproull, president of the University (formerly founding director of the U.S. Advanced Research Projects Agency), and funding from the University of Rochester, New York State, and corporations that included General Electric, Exxon Nuclear, Northeast Utilities, and Empire State Electric Research Corporation, the small research team built their first large laser, the four-beam DELTA. The DELTA was a neodymium glass laser used to investigate the interaction of high-power laser radiation and matter with particular emphasis on laser-fusion development. The LFFP consortium eventually attracted several other corporate sponsors, including Southern California Edison, Standard Oil of Ohio (SOHIO), and Ontario Hydro.

During this period, Professor Len Goldman, Moshe Lubin, and John Soures, one of the first graduates of LLE who later became its first Experimental Division Director, published the results of DELTA experiments showing the saturation of radiation in laser plasmas and other LLE investigations of short pulse laser–heated fusion plasmas [L. M. Goldman, J. Soures, and M. J. Lubin, "Saturation of Stimulated Backscattered Radiation in Laser Plasmas," Phys. Rev. Lett. **31** (19), 1184–1187 (1973)]. Also, Edward Goldman, who headed the LLE theory effort at that time, published results on numerical modeling at laser–target interactions [E. B. Goldman, "Numerical Modeling of Laser Produced Plasmas: The Dynamics and Neutron Production in Dense Spherically Symmetric Plasmas," Plasma Phys. **15**, 289–310 (1973)].

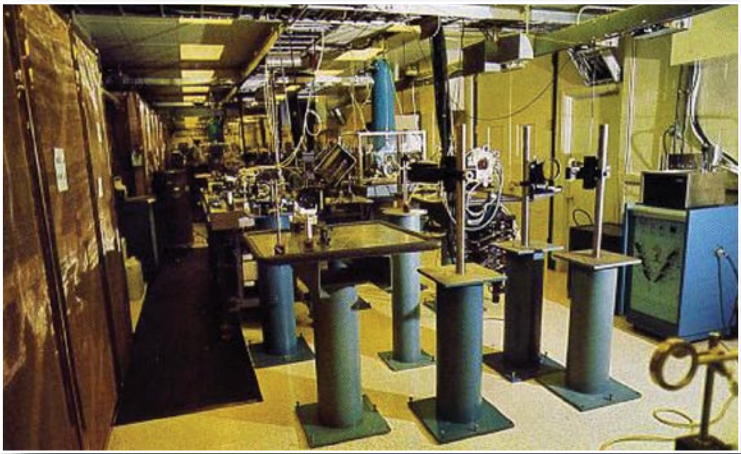


Figure 4.5: The LLE four-beam DELTA laser was one of the earliest laser-fusion experimental facilities.

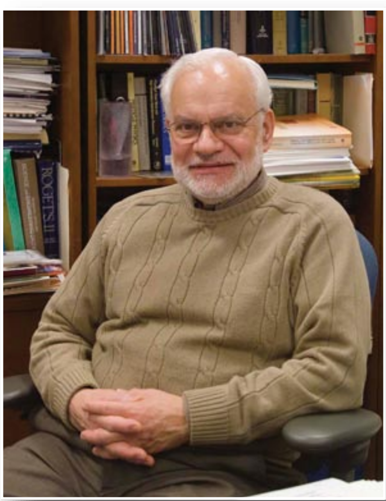


Figure 4.6: John Soures, one of the first graduates of LLE (1970), was its first Experimental Division Director.

Other major laser-fusion projects were starting elsewhere, as well. For example, Lawrence Livermore National Laboratory was building what they called the Longpath Laser. The Russians, French, Germans, British, and Japanese were all conducting early research into the use of lasers to generate fusion energy.

By 1975, it was clear that the vision of the Lubin team—to build and operate a very large, 24-beam infrared laser facility to be called OMEGA—would cost tens of millions of dollars. The University of Rochester, New York State, and private industry could contribute just so much. Robert Sproull asked Don Hess (who had just joined the University as Vice President for Administration and, prior to that, had served as Director of the U.S. Peace Corps) to assist in securing funding from the federal government.

Lubin, Sproull, and Hess managed to slot Lubin into a hearing held by the Joint House–Senate Committee on Atomic Energy. Lubin was to be the last person to appear before the Committee. But at the last minute the Committee changed the order of the people who would come before it, and Lubin was next-to-last to testify. Dr. Keeve Siegel, president of a Michigan contract company, would be last.

Lubin testified on behalf of LLE, and then Dr. Siegel began his testimony. About two minutes into his presentation, Dr. Siegel had a stroke and died. The Committee immediately adjourned.

Had the Committee not changed the order of those appearing before it, Lubin may never have gotten his chance to request federal funding for LLE. As it was, the U.S. Government ended up providing an adequate amount of funding for inertial confinement fusion research at LLE. With the additional funding, research and development proceeded quickly.

LLE Director and CEO Robert L. McCrory joined the effort in 1976. He recalls that during the period from 1975 to 1980, the one-beam Glass Development Laser (GDL), six-beam ZETA, and 24-beam OMEGA laser systems were constructed.

Figure 4.7: Director Robert McCrory joined LLE in 1976 and was its first Theoretical Division Director. He is now serving as Vice Provost, University of Rochester and is Professor of Physics and Astronomy and Professor of Mechanical Engineering.

The GDL was a prototype for OMEGA, and ZETA was a proof-of-design system incorporating the first six beams.

The Laboratory was dedicated in October 1978 in its ZETA configuration. 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 gas shell.

Figure 4.8: U.S. Representative Frank Horton pushed the button to fire the first six beams of OMEGA in an actual target shot that took place during the dedication ceremonies in 1978.

In 1980, the OMEGA 24-beam system was officially operational. A key aspect of the OMEGA design was Nd:phosphate glass. Steve Jacobs (Senior Scientist at LLE and Professor at The Institute of Optics and Department of Chemical Engineering) succeeded in developing a strong collaboration with Hoya Optics that led to the development of a phosphate laser glass (LHG-8) that was particularly suitable for fusion laser systems. He was one of the members of the Glass Laser Development Group, led by John Soures and including Wayne Knox, then a student, now Director of The Institute of Optics. This team carried out much of the development work that eventually led to the GDL, ZETA, and OMEGA lasers, large-aperture laser amplifiers, the demonstration of high-efficiency frequency tripling, and beam-smoothing technology development.

Figure 4.9: Stephen Jacobs was key in the development of the laser glass used on the OMEGA laser and leads the optical materials effort at LLE.

Figure 4.10: Wayne Knox did his Ph.D. research work at LLE in the 1970s and is now Director of the Institute of Optics.

An essential element in the successful implementation of the OMEGA laser was a highly integrated engineering effort. Jay Eastman was project manager for the construction of OMEGA, and he worked with an extremely innovative group of LLE engineers and scientists, as well as a large team of engineers and managers from the Eastman Kodak Company, in bringing this project to fruition. He became director of LLE upon the departure of LLE's founder, Moshe Lubin, in 1981. Eastman left the laboratory in 1982 to start a private company (Optel) specializing in bar-code scanners and is now the CEO of Lucid, a Rochester-based medical device and information company. This was one of the many successful examples of the transfer of LLE-developed technology to the private sector.

The 24-beam OMEGA went through three phases. The first was the prototype system with only two laser beams. Then came a six-beam implementation of the hardware, and finally, in the third phase, came the 24-beam OMEGA. The laser system was used not only for fusion experiments, but also, LLE began operating as a National Laser Users' Facility (NLUF) for laser–matter interaction studies by scientists from all over the country. To this day, LLE functions in both manners: for inertial confinement fusion experiments and for NLUF studies that use the high-energy-density capabilities of the LLE lasers.

Figure 4.11: Jay Eastman was the Project Manager for the 24-beam OMEGA laser.

Figure 4.12: The original 24-beam OMEGA laser shown in its UV configuration (circa 1985).

A laser generates a single color or wavelength, and the power of the laser is concentrated at this particular wavelength. The shorter the wavelength of the light, the more penetrating the laser beam. And the shorter the wavelength of the light, the denser the plasma that absorbs it.

When laser light of a particular intensity impacts matter, the light is absorbed by the matter. However, the amount of absorption depends on the wavelength of the light. Shorter-wavelength laser light (in other words, bluer light) results in more absorption of the light energy at higher densities.

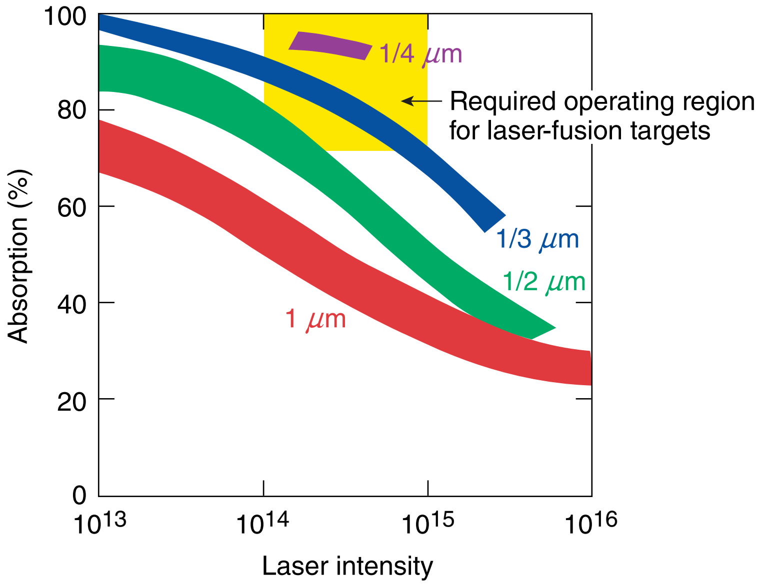


Figure 4.13: Early laser–matter interaction experiments showed that short-wavelength laser radiation was absorbed more efficiently by laser-fusion targets.

In the early-to-mid 1970s, scientists realized that to make fusion work, very short wavelengths—high-focused light intensities—were needed, resulting in high-energy density. About the same time as OMEGA started operations, LLE discovered that it is possible to shorten a laser's output wavelength, which gives the laser significantly increased effectiveness.

A scheme for *frequency conversion* was created and patented by LLE in 1980 and became a standard for fusion lasers all over the world. The integrated theoretical and experimental team responsible for this very important result was led by Steve Craxton (lead theoretical physicist–now Senior Scientist) and Wolf Seka (lead experimental physicist–now Senior Scientist). It was an elegant approach conceived by Craxton that led to this breakthrough. The approach uses a KDP (potassium-dihydrogen-phosphate) crystal to convert approximately two-thirds of the energy of a Nd:glass laser's output at a wavelength of 1.054 micrometers to its second harmonic in a wavelength of 0.532 micrometers. The remaining 1.054 micrometers of light is mixed with the second-harmonic light in a second crystal to produce the third harmonic of 0.351 micrometers. By properly choosing the crystal orientations and laser polarization, it was demonstrated that over 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 in coupling into and driving an inertial confinement fusion target implosion than infrared light, this invention was akin to boosting the energy of existing glass lasers by nearly an order of magnitude.

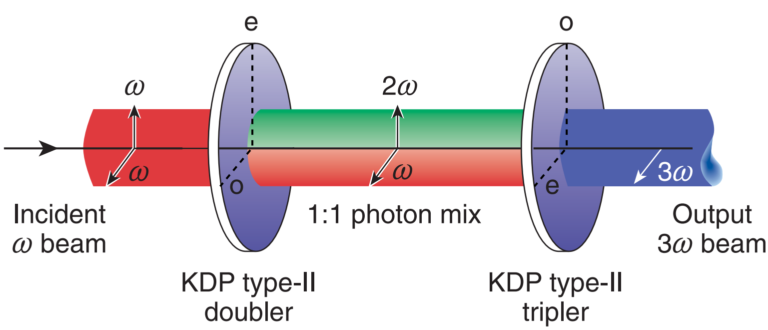


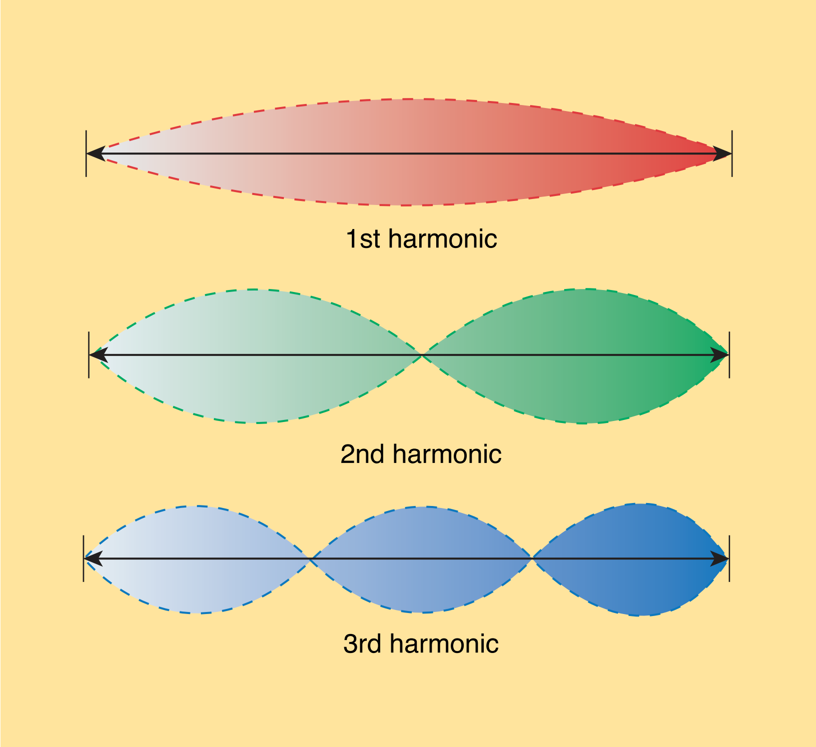
Figure 4.14: Schematic illustrating the polarization mismatch frequency-conversion scheme invented by Stephen Craxton in 1980.

Figure 4.15: Stephen Craxton (top left) and Wolf Seka (top right) led the LLE effort to develop an efficient frequency-conversion scheme. The full 24-beam OMEGA laser was frequency converted in 1985 (bottom).

Figure 4.16: Beam splitting, amplification, and frequency tripling of the pre-1992 OMEGA 24-beam OMEGA laser were carried out in the large room shown above. 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 boxlike 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. [R. S. Craxton, R. L. McCrory, and J. M. Soures, “Progress in Laser Fusion,” Sci. Am. **255**, 68–79 (2) (1986).]

What are Harmonics?

A *harmonic* is an oscillation with a frequency that is a simple multiple of a first, or fundamental, frequency. The fundamental frequency is also called the *first harmonic*. When the fundamental frequency is multiplied by two, the result is a *second harmonic*, which has twice the frequency of the first harmonic. This *third harmonic* has three times the frequency of the first harmonic.



In 1983, Robert L. McCrory was appointed Director of LLE. By the end of 1985, the full 24-beam ultraviolet conversion of OMEGA was completed. From 1983 to 1987, significant work was carried out at LLE on characterizing the physics of ultraviolet laser–matter interaction, developing tools for the design of high-performance direct-drive targets, and developing high-density plasma diagnostics and direct-drive target-fabrication facilities.

In 1986, the National Academy of Sciences reviewed the Department of Energy's Inertial Confinement Fusion Program. The report recognized the work done by LLE in addressing the key aspects of inertial confinement fusion. DOE 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 kilojoules.

As part of its response, LLE installed a *cryogenic target system* on OMEGA that allowed for thin layers (10 micrometers) inside relatively small (380 micrometer diameter) DT-filled (75 to 100 atmospheres) glass shells. The targets were supported by spider silk drawn across a U-shaped copper mount. Another area of work focused on improving the laser-beam irradiation uniformity.

Through the efforts of the Optical Engineering Group led by Terrance Kessler (leader of the Optical and Imaging Sciences Group), phase conversion using specially constructed "distributed phase plates" (DPP's for short) was implemented on OMEGA to improve the uniformity of the beams on target. These plates essentially divided each laser beam into thousands of smaller beamlets. These were collectively focused by the OMEGA focusing lenses into relatively large round spots that produced more uniform laser-energy-intensity distributions on target than had been previously possible.

Figure 4.17: Terrance Kessler was responsible for the development and implementation of phase conversion on OMEGA and leads The Optical and Imaging Sciences Group at LLE.

As a result of 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 [R. L. McCrory *et al.*, "Laser-Driven Implosion of Thermonuclear Fuel to 20 to 40 g cm^{-3}," Nature **335** (6187), 225–230 (1988)].

In 1988, an independent Department of Energy panel reviewed the results of the high-density experiments and confirmed that LLE had achieved the highest compressed fuel density ever recorded in an inertial confinement fusion experiment, using either the direct or indirect-drive approach

On the heels of the high-density milestone achievement, LLE scientists achieved another breakthrough in 1989 with the development and demonstration on OMEGA of a new type of beam-smoothing technique—"smoothing by spectral dispersion" (SSD). SSD combines phase conversion (previously described, p. 47) with time-varying phase modulation of the laser beam to effectively time-blur the intense hot spots left in the beam after the beam is phase converted using DPP's. Once again, an integrated team made up of theoretical and experimental scientists and engineers tackled and solved this problem. The team included Stan Skupsky (at that time, Group Leader of the Theory Group, now serving as Theoretical Division Director), Robert Short (Group Leader for Plasma Physics), Sam Letzring (at that time, serving as Group Leader for Diagnostics Development, now a scientist at Los Alamos National Laboratory), in addition to Kessler, Craxton, and Soures. Skupsky and Soures shared the American Physical Society 1993 Award for

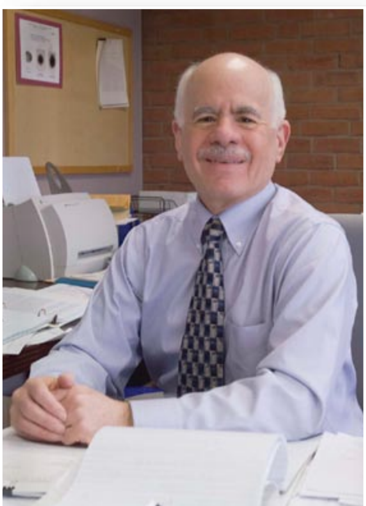


Figure 4.18: Stanley Skupsky made major contributions to beam smoothing for direct-drive ICF targets and is the LLE Theory Division Director.

Excellence in Plasma Physics Research with scientists from the Naval Research Laboratory and Osaka University for the development and application of advanced beam-smoothing techniques for laser-fusion experiments.

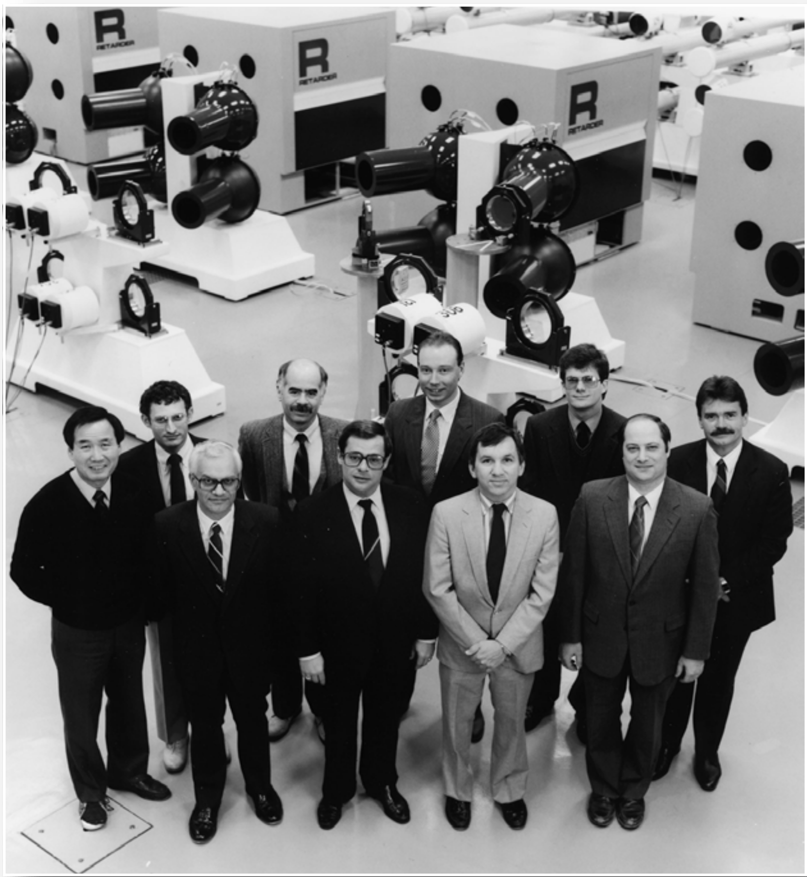


Figure 4.19: The team responsible for achieving the first LLE high-density cryogenic target milestone in 1988. Left to right: Hyo-gun Kim, Stephen Jacobs, John Soures, Stanley Skupsky, Robert McCrory, Frederick Marshall, Samuel Letzring, Terrance Kessler, James Knauer, and Robert Hutchison.

LLE received a second APS Award for Excellence in Plasma Physics Research in 1995, when James Knauer (Senior Scientist in the Experimental Division) and Charles Verdon (LLE's Theory Division Director at that time, now serving as AX Division Leader at LLNL) shared the prize with scientists from LLNL for outstanding theoretical and experimental work on Rayleigh–Taylor instability (RTI) in high-energy-density plasmas. 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 due to 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 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.

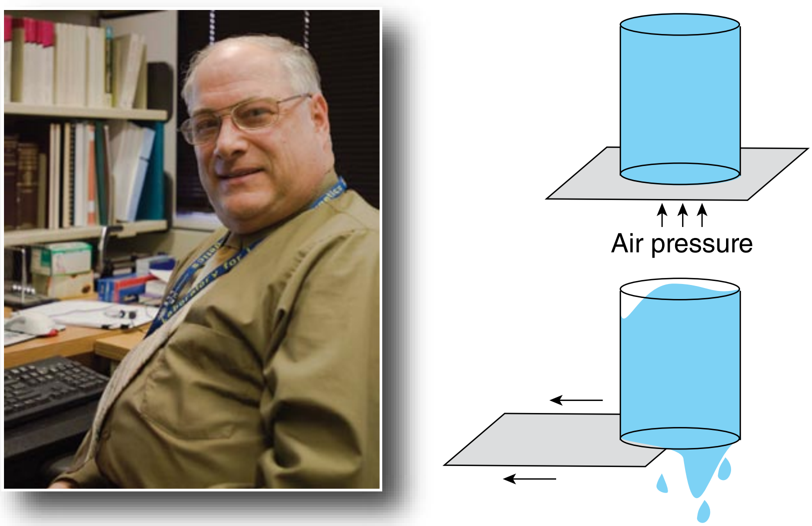


Figure 4.20: James Knauer was a co-recipient of the 1995 APS Award for Excellence in Plasma Physics Research for his experimental work on Rayleigh–Taylor instability (RTI). One of the many natural manifestations of RTI is illustrated by the inverted glass demonstration.

On the basis of the high-density-compression results and the advances in beam-smoothing technology, and after a congressionally mandated review of the ICF program by the National Academy of Sciences in 1989, LLE received the go-ahead to design and construct an upgrade to the OMEGA Laser Facility. In the late 1980s and early 1990s, LLE worked on the OMEGA Upgrade laser; it was designed to be a 60-beam ultraviolet laser with energy-on-target capability of 30 kilojoules. To maximize its experimental utility, the system was designed to shoot at least one laser shot per hour.

In December 1992, the 24-beam OMEGA laser fired its last shot. Then in March 1995, the first full 60-beam laser shot was fired, and in April 1995, all 60 OMEGA beams irradiated a target.

From its first shots in 1995, the OMEGA Upgrade set the standard for inertial confinement fusion research. In its first experimental campaign with DT-fuel targets, OMEGA produced fusion neutron yields in excess of one hundred trillion neutrons—corresponding to a fusion-energy release of approximately 1% of the laser incident on the target. Patrick McKenty (Group Leader of the Computational Design Group) was the lead theoretician for these experiments.

As of the writing of this book (2008), the record remains, but it will probably be eclipsed by future experiments on the National Ignition Facility between 2010 and 2012.

Figure 4.21: 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.

In 1990, Captain Steven J. Loucks (USN, Ret.), a former nuclear submarine commander, joined LLE as Administrative Division Director. By 1994, Steve assumed the direction of the LLE Division of Engineering. He was key to the successful completion of the OMEGA Upgrade project on time and budget, and he organized a highly effective operating regimen for the facility that continues to this day.

Figure 4.22: 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.

In 1996, OMEGA began to provide laser shots for indirect drive and other high-energy-density physics experiments from the national laboratories: Los Alamos National Laboratory, Lawrence Livermore National Laboratory, and Sandia National Laboratory. The system's flexibility was amply demonstrated by carrying out high-quality hohlraum-driven target implosions with 40 of its beams configured to irradiate cylindrical hohlraums.

In recent years, the Commisariat à l'Énergie Atomique (CEA) of France and the Atomic Weapons Establishment (AWE) of the United Kingdom have also become regular users of the OMEGA facility.

Since the OMEGA upgrade in 1995, the shot productivity of the LLE OMEGA Laser Facility has been exceptional. Approximately 1,500 target shots are taken each year, and approximately half are taken by external users such as national laboratories. Keith Thorp serves as the OMEGA Laser Facility Manager.

Figure 4.23: Keith Thorp is the OMEGA Laser Facility Manager.

An important part of the LLE program has been the National Laser Users' Facility, which was established in 1979 to provide U.S. scientists access to LLE's high-powered laser facilities. More than 291 proposals have been submitted to use the LLE laser facilities, and of these, 154 have been accepted. Participants have included scientists from some 40 universities, government laboratories, and private companies. Current research programs include inertial fusion, laser–matter interaction, high-energy-density materials, laboratory astrophysics, high-energy-density plasma-diagnostics development, and atomic physics.

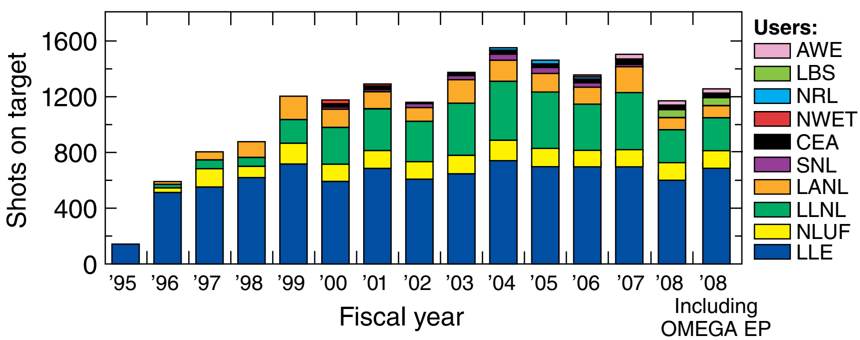


Figure 4.24: Over 15,000 target shots have been carried out on OMEGA since 1995.

Nuclear Fusion at LLE: Now and in the Future

With the one exception of the 192-beam NIF laser soon to be operational at Lawrence Livermore National Laboratory (LLNL), the world's most powerful experimental laser facility currently operating is the OMEGA laser at LLE, which delivers more than 30 kilojoules of ultraviolet laser light to a target in pulses one billionth of a second in duration.

The National Ignition Facility (NIF), currently under construction at Lawrence Livermore National Laboratory, is expected to deliver more than 30 times the energy to a target than OMEGA. The NIF, which will be completed in 2009, will deliver 1.0 megajoules of ultraviolet light to a target. Due to the large diameter of the NIF (40 centimeters), the time between laser shots at the NIF is expected to be several hours. At LLE, the time between laser shots is approximately 45 minutes.

The current plan is to use the NIF for experiments requiring the NIF's high-energy capabilities. Other experiments, as well as eventual NIF experiments that are in early conceptual stages, will be carried out at LLE. Engineers and scientists from LLE have been collaborating with Lawrence Livermore National Laboratory since the earliest NIF design phases.

Other than the NIF, the only other facility of this magnitude being developed in the world is the Laser Megajoule (LMJ) Facility currently under construction at the Commisariat à l'Énergie Atomique (CEA) in Bordeaux, France. This facility will be completed in approximately 2013. Scientists from CEA have been conducting experiments on OMEGA to develop diagnostics and test design calculations for future LMJ experiments.

LLE remains at the forefront of inertial confinement fusion research. It is at LLE that many major breakthroughs have occurred and are currently taking place in the field: *frequency conversion*, *beam smoothing*, *chirped-pulsed amplification*, and *cryogenic target* techniques.

In fact, in 2008, LLE passed a major Department of Energy milestone: direct-drive cryogenic targets with similar design characteristics as those that will eventually be used to demonstrate ignition on the NIF were successfully compressed to an areal density (that is, density × radius) of 200 milligrams per square centimeter. These targets achieved a compressed fuel density of over 500 times that of liquid deuterium (approximately four times the density achieved in the first LLE cryogenic experiments in 1989). This is 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.

Figure 4.25: 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 recent OMEGA cryogenic target implosion experiments that achieved a record fuel areal density of 200 mg/cm^2 and compressed density of over 100 g/cm^3.

In the meantime, the OMEGA Extended Performance (EP) System, under development since 2001 at LLE, will deliver more than a kilojoule of energy to a target in a picosecond, which is 10^{-12} seconds. That corresponds to a laser power of one petawatt, or one thousand terrawatts. The laser will have the capability of generating over 2,600 joules in 10 picoseconds in one beam, making it the world's most energetic short-pulse beam.

Since the typical power of the entire U.S. electrical grid is approximately 1 terawatt, which is 10^{12} watts, OMEGA EP will supply more power in a brief instant of time than 1,000 times the entire U.S. electrical grid.

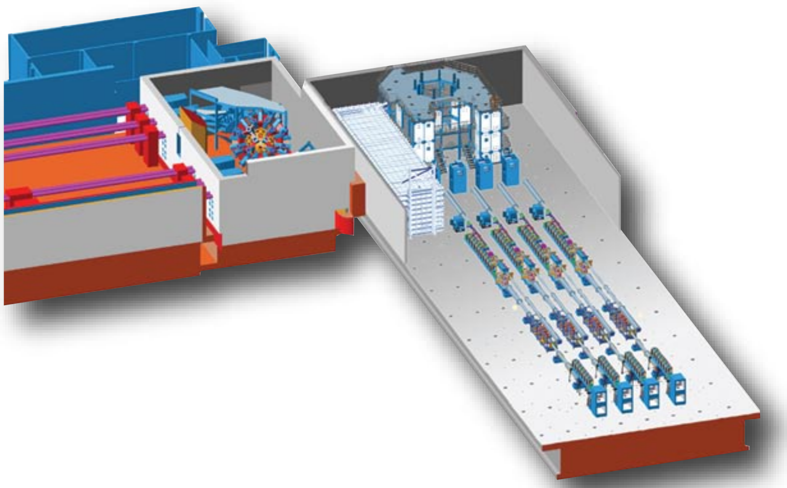


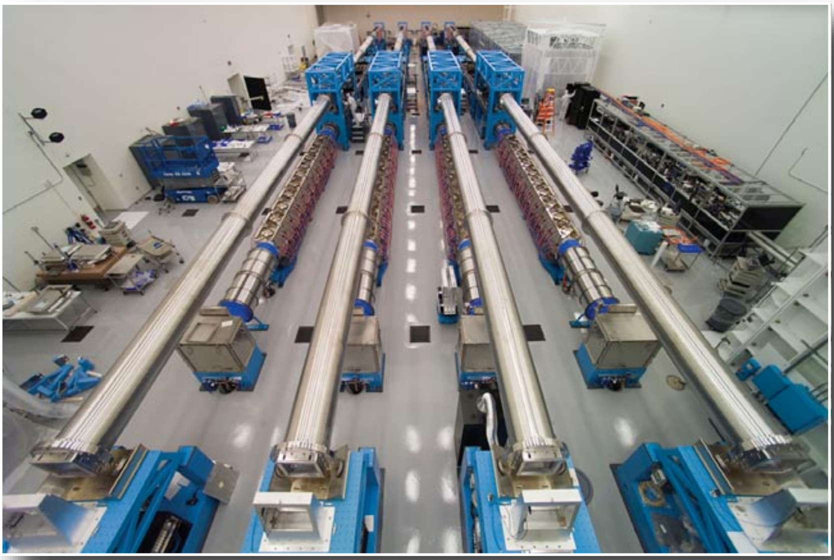
Figure 4.26: Artistic rendering of the OMEGA EP and OMEGA lasers.

OMEGA EP started operations in mid-2008 and has the mission of (a) providing intense short-pulse bursts of x rays to probe OMEGA cryogenic target compressions, (b) exploring advanced schemes to achieve ignition and high fusion gain, and (c) exploring the broad range of high-energy-density physics that characterize ultrahigh-intensity laser–matter interactions. Sam Morse was the OMEGA EP Project Manager and is now OMEGA Facility Director.

Figure 4.27: Samuel Morse is the OMEGA Facility Director.

Figure 4.28: Douglas Jacobs-Perkins is the Engineering Division Director and LLE's Chief Safety Officer.

Recent photos of OMEGA EP



View of the OMEGA EP Laser Bay.

View of the OMEGA EP Target Chamber area.

OMEGA EP uses a *chirped-pulsed–amplification* (CPA) technique developed at LLE in the late 1980s by Gerard Mourou (at that time Group Leader of the LLE Ultrafast Science Group, now the Director of the Laboratoire d'Optique Appliquée in France) and Donna Strickland (at that time, a graduate student at LLE, now a professor at the University of Waterloo in Canada). With the CPA method, the laser pulse is first 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} watts per centimeter squared, 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.

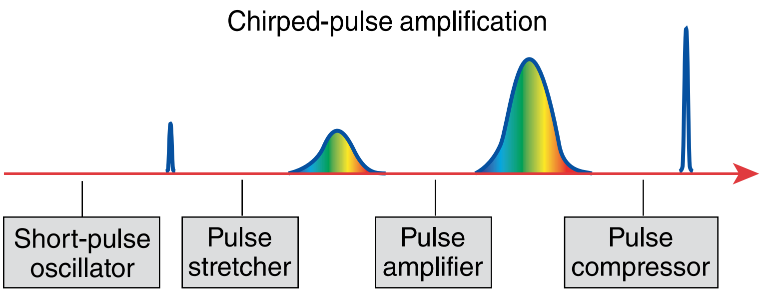


Figure 4.29: Chirped-pulse amplification is used to produce very-high-intensity ultrashort laser pulses.

One of the advanced fusion-ignition techniques to be explored at the OMEGA Facility will be "fast ignition". The OMEGA 60-beam laser will compress the thermonuclear fuel to densities of hundreds of grams per cubic centimeter. The compressed fuel (spark) 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 and trigger the spark. A burn wave will then propagate from the spark throughout the fuel, causing the thermonuclear ignition of the entire fuel assembly.

If successful, fast ignition could lead to the highest energy densities and inertial confinement fusion conditions ever achieved in a laboratory.

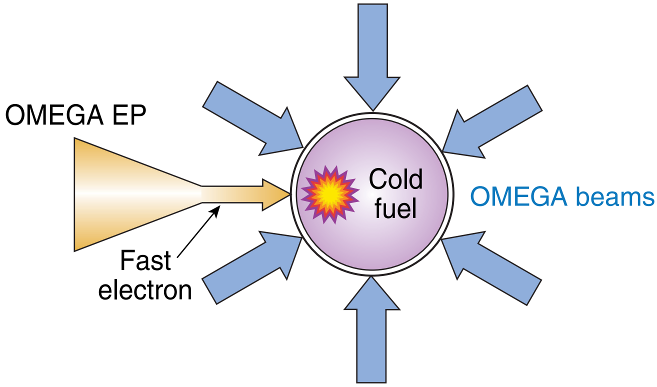


Figure 4.30: Schematic illustrating the fast-ignition process.

Fast ignition is a very promising path to inertial confinement fusion energy. It separates the compression from the heating and lowers the total required laser energy. By using a high-energy driver that needs only to compress the fuel without heating it, the fast-ignition scheme can achieve fusion conditions with a smaller high-energy driver than required in the standard inertial confinement fusion approach. Since the compressed fuel density is predicted to reach 200 grams per cubic centimeter and a temperature of 70 million degrees centigrade, the energy density will approach 10^5 megajoules per cubic centimeter, or 1000 gigabars. The fundamental physics of fast ignition and other advanced fusion schemes are 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.

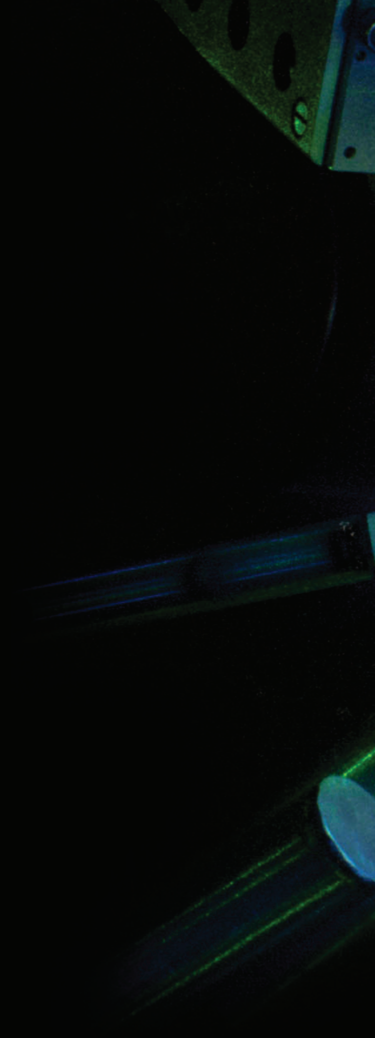
Figure 4.31: Riccardo Betti (left), along with David Meyerhofer, co-direct the UR Fusion Science Center (FSC) for Extreme States of Matter and Fast-Ignition Physics.

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 also 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.

The world is taking notice of nuclear fusion as tomorrow's energy source. Scientists expect that one kilogram of fusion fuel will generate the same amount of power as 10,000,000 kilograms of today's fuel.

Decades of research have gone into the science that lets us create a nuclear fusion power plant. ***This research is centered at facilities such as LLE—one of the most prominent nuclear fusion centers in the world.***

Nuclear fusion gives us the energy of the Sun and the stars—literally.



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