



Accelerators AND Beams

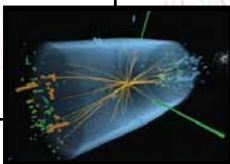
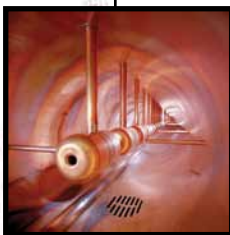
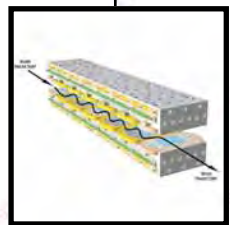
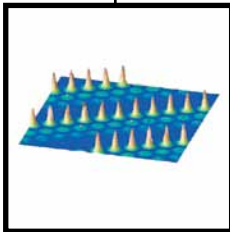
TOOLS OF DISCOVERY AND INNOVATION

4th Edition

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Accelerators AND Beams



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CREDITS TOP TO BOTTOM: BROOKHAVEN'S NATIONAL SYNCHROTRON LIGHT SOURCE; OAK RIDGE NATIONAL LABORATORY SPALLATION NEUTRON SOURCE; WILSON LABORATORY, CORNELL UNIVERSITY; FERMILAB; CERN.

Why care about accelerators?

COURTESY FERMILAB.



Fermilab in Illinois has been the site of many advances in the dynamic, evolving field of high-energy physics, which probes the tiniest sub-microscopic realms. This premier laboratory of American science, now in a transition period, has made major contributions to new knowledge of matter itself. (Red lines indicate particle paths.)

COURTESY BROOKHAVEN NATIONAL LABORATORY.



The Advanced Photon Source at Argonne National Laboratory near Chicago (R) and the National Synchrotron Light Source at Brookhaven National Laboratory on Long Island (L) deliver intense, tightly focused beams of X-rays as well as ultraviolet and infrared radiation. Researchers from across the nation use these accelerator-based facilities for basic and applied research in many fields.

Research using beams from particle accelerators has told us much of what we know about the basic building blocks of matter, and about nature's fundamental forces.

In controlled laboratory settings, the highest-energy accelerators — physically the largest — recreate conditions that have not occurred since the Big Bang. Such accelerators probe nature's deepest mysteries. They are central in the effort to unravel the mysteries of dark matter and dark energy.

But that's only part of the reason to care.

Many thousands of accelerators, most of them only room-sized or smaller, serve as essential tools for biomedical and materials research, for diagnosing and treating illnesses, and for a growing host of tasks in manufacturing, in energy technology, and in homeland security.



COURTESY ARGONNE NATIONAL LABORATORY.

What are accelerators for?

Particle accelerators are essential tools of modern science and technology.

About 10,000 cancer patients are treated every day in the United States with beams from accelerators. Accelerators also produce short-lived radioisotopes that are used in over 10 million diagnostic medical procedures and 100 million laboratory tests every year. Nuclear diagnostic medicine and radiation therapy together save countless lives and generate about \$20 billion in business annually. An accelerator produces your dental X-rays.

The multi-billion-dollar semiconductor industry relies on ion beams from accelerators to add special atoms in semiconductors. Ion implantation is also used to produce hard surface layers in artificial hip or knee joints, high-speed bearings, and cutting tools.

X-ray lithography with intense beams etches microchips and other semiconductor devices.

Accelerators are used for accurate, nondestructive dating of archeological samples and art objects, for unraveling DNA structure, and for pharmaceutical research. Accelerators provide promising potential avenues towards solving energy problems.



COURTESY DEPARTMENT OF RADIATION ONCOLOGY, STANFORD UNIVERSITY.

Patients receive state-of-the-art radiation therapy with beams from accelerators.



COURTESY STANFORD SYNCHROTRON RADIATION LIGHT SOURCE.

Long after Archimedes wrote on a parchment 23 centuries ago, others superimposed new words and later paint. Recently a Stanford University accelerator enabled scholars to read the original text — a founding document for all of science.

What is an accelerator?

A particle accelerator is a scientific instrument that produces a directional stream of electrically charged particles, usually electrons or protons. The accelerator also boosts the energy of this beam.

Particle beams are used for many kinds of research, and for medical and industrial applications.

There are two families of accelerators.

In **linear** accelerators, also called *linacs*, the beam usually passes only once through the accelerating fields and magnetic focusing fields, though recirculating linacs bring the beam back around for a few extra acceleration passes.

In **circular** accelerators — cyclotrons and synchrotrons — magnetic fields bend the particles' path so that the particle beam passes repeatedly through the accelerating structures and focusing magnets.

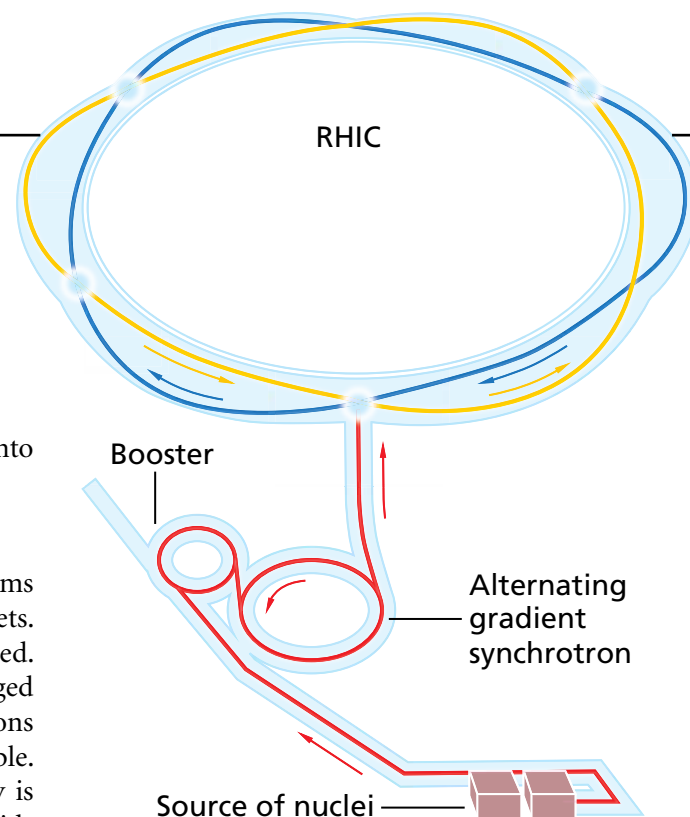
These families can each be divided into two more families:

Fixed target

Fixed-target accelerators shoot beams of moving particles at stationary targets. Almost any type of target can be selected. Many different types of electrically charged particles can be accelerated, including ions from every element in the periodic table. In physics research, the target typically is a piece of metal, or a gas-filled or liquid-filled tank. In other applications, it might be anything from a cancerous tumor needing treatment to a metal surface needing hardening.

Colliding beam

In colliding-beam accelerators, two beams of high-energy particles collide head-on. Far higher energies can be generated in colliding-beam accelerators than in fixed-target scenarios, because the total energy in both beams is available. In a circular collider, beams orbiting in opposite directions collide at one or more locations in the ring. (However, the number of collisions per second is far less than with a fixed target.)



A chain of accelerators makes up the Relativistic Heavy Ion Collider at Brookhaven National Laboratory on Long Island. Each accelerator feeds a beam into the next higher-energy machine.

Since this is a collider, a beam from the Alternating Gradient Synchrotron is injected into the yellow ring and into the blue ring. Nuclei travel in opposite directions in these two rings and collide at the four points indicated. This is where experimenters observe the collisions.

On page 9 is an image of a collision between the nuclei of gold atoms in this collider.

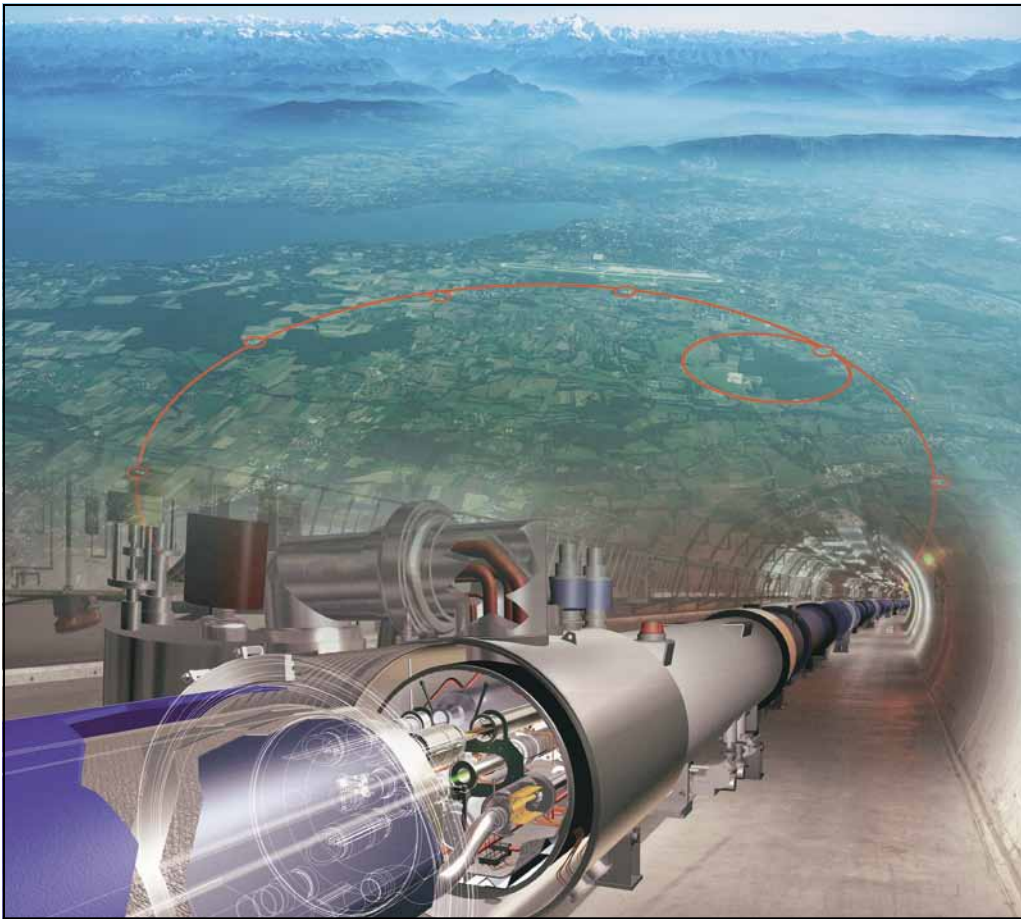
The invention of

In the earliest particle accelerators a static electric field accelerated charged particles to higher energies than conventional voltage sources could deliver. In the 1920's the work of Rolf Wideröe, a Norwegian engineer, led directly toward the modern linear accelerator.

Wideröe's work also intrigued Ernest O. Lawrence, a young scientist at the University of California at Berkeley. In the 1930's, Lawrence became the first to apply the work to a circular accelerator when he invented the cyclotron.

The cyclotron opened up whole new avenues of research in nuclear physics, including the production of unstable nuclei and non-naturally occurring elements. It also enabled particle-beam treatment of cancer.

Since then, advances in technology have driven a million-fold increase in accelerator energies, which now exceed 3 trillion volts. The field has progressed from accelerator beams that strike stationary targets to accelerators with counter-rotating beams called colliders. The beams collide head-on and make full use of both beams' energy.



COPYRIGHT CERN.

The Large Hadron Collider (LHC) — straddling the Swiss-French border near Geneva — has embarked on a new era of discovery. Experiments there investigate what gives matter its mass, what makes up the invisible 95% of the universe, why nature prefers matter to antimatter, and how matter evolved from the first instants of the universe's existence. In 2012 LHC researchers discovered what is believed to be the Higgs boson, a particle that is required to explain mass.

US scientists and engineers, supported by the US Department of Energy Office of Science and the National Science Foundation, participated in the construction of the LHC. More than 1,700 people from 94 American universities and laboratories have joined with scientific colleagues from around the world to collaborate on LHC experiments at the horizon of discovery. The US financial contribution to this global project is in excess of \$500 million.

particle accelerators

The biggest accelerators stretch for miles.

The Large Hadron Collider, called the *LHC*, a proton-proton collider in Europe, is the world's highest-energy particle accelerator.

The Relativistic Heavy Ion Collider at Brookhaven National Laboratory collides gold nuclei with each other.

The Fermilab Tevatron in Illinois, until recently the world's highest-energy accelerator, was shut down in 2011. It collided protons with antiprotons and produced the top quark, the most massive elementary particle known.

These are among the grandest scientific instruments ever built.

COURTESY LAWRENCE BERKELEY NATIONAL LABORATORY.
ROY KALTSCHMIDT, PHOTOGRAPHER.



Lawrence's first cyclotron.

COURTESY LAWRENCE BERKELEY NATIONAL LABORATORY.



Nobel laureate Ernest Orlando Lawrence in 1939.

COURTESY FERMILAB.



Robert Rathbun Wilson at the Fermilab Main Ring groundbreaking in 1969, for what became in 1972 the world's highest-energy proton accelerator.

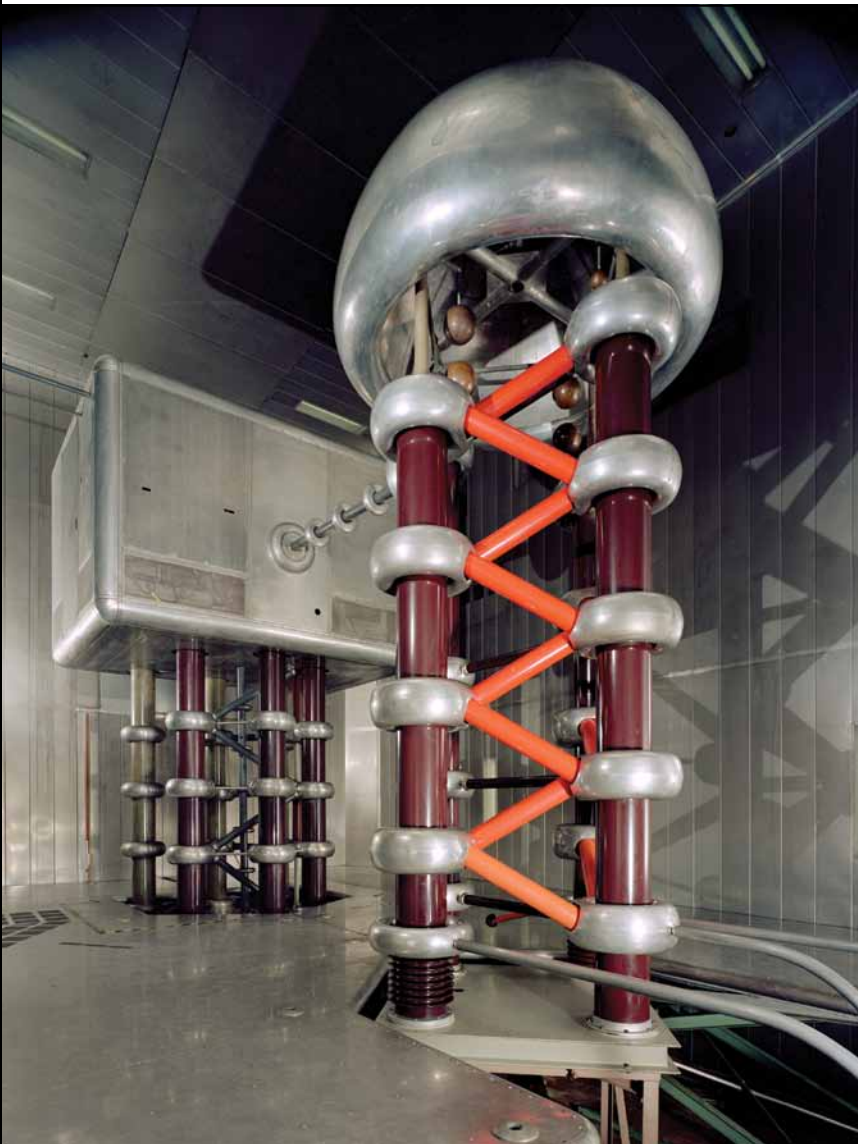
COURTESY WILSON LABORATORY, CORNELL UNIVERSITY.



Nobel laureate Hans Bethe and accelerator physicist Boyce McDaniel in 1968 in Cornell's half-mile-circumference accelerator tunnel.

How accelerators work

An accelerator's intended use dictates selection of the charged-particle beam's characteristics. The particles are always electrically charged: electrons, positrons (anti-electrons), protons, antiprotons, various nuclei or ions (atoms with an imbalance of electrons and protons). To create a large accelerator for discovery science, accelerator physicists work with engineers to design, build, install, commission and operate components like those described here and on the facing page. (Industrial and medical accelerators are much smaller.)



COURTESY ARGONNE NATIONAL LABORATORY

A. The charged particle source and high-voltage preaccelerator in the Intense Pulsed Neutron Source at Argonne National Laboratory.



COURTESY JEFFERSON LABORATORY

B, C. Magnets and vacuum chambers at Jefferson Laboratory. Visible here are a focusing magnet (red), a bending magnet (light blue) and the stainless steel vacuum chamber (beam pipe).



COURTESY CERN

C. An engineer checks the electronics of the instrumentation under a dipole magnet in the Large Hadron Collider.

A. The source produces the charged particles to be accelerated.

B. Vacuum chamber. The beam travels through a pipe evacuated to as low a pressure as possible to minimize scattering of the beam particles by gas particles that remain in the pipe.

C. Magnets bend the particles along the correct path and keep them concentrated in a narrow beam.

D. Accelerating structures. Electric fields accelerate the beam.

E. Cooling systems. Either water or ultra-low-temperature liquid helium removes heat dissipated in accelerator components. Superconducting magnets and accelerating structures require liquid helium to achieve superconductivity.

F. Injection/extraction systems guide particles into/out of the accelerator or from one accelerator to another.

G. Beam diagnostics provide information about the beam intensity (current), position, beam profile, and beam loss. The information is transmitted to a control room. Many accelerators have an enormous amount of energy in the beam. A special subsystem can nearly instantly detect malfunctions and trigger special magnets to “dump” the beam at a safe location to prevent damage to the accelerator.

COURTESY JEFFERSON LABORATORY.



D. Accelerating structure. Electric fields in the sequence of cells in this superconducting accelerating structure “kick” the particle beam to ever-higher energy as it passes through on its way to more such structures. The pictured kind of accelerating structure operates superconductively, with almost no electrical resistance, by being cooled nearly to absolute zero. Superconducting operation saves enormously on the power bill.

COURTESY FERMILAB.



E. Magnets cooled by liquid helium in the Tevatron at Fermilab.

COURTESY FERMILAB.



F. Injection/extraction. Beam line transfers particles between two accelerator rings in the Fermilab antiproton source.

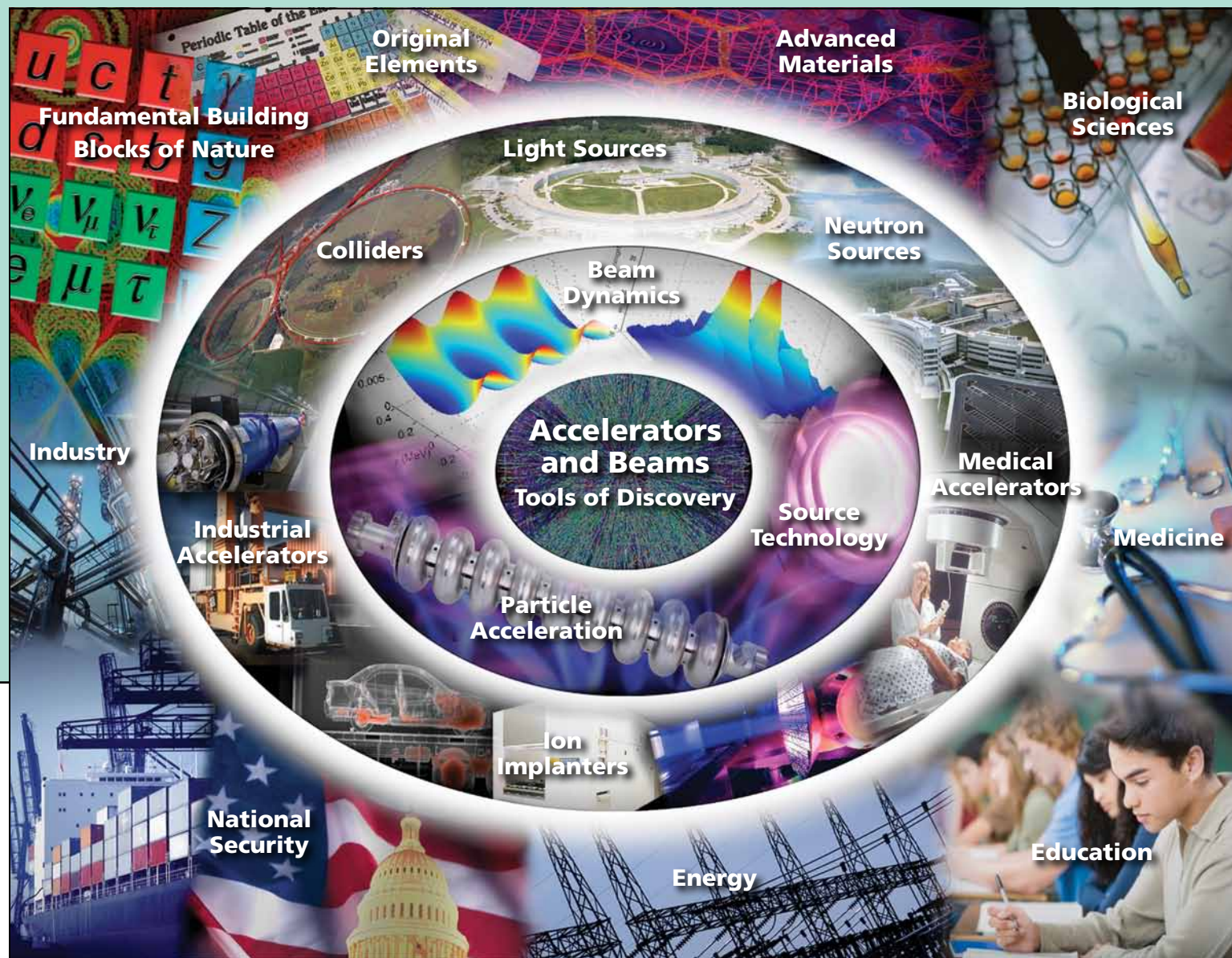
COURTESY JEFFERSON LABORATORY.



G. Jefferson Laboratory accelerator control center.

Applications of accelerators

COURTESY OAK RIDGE NATIONAL LABORATORY.



Illuminating what
our eyes do not see
and manipulating
what our hands cannot

The world has only a few
huge, expensive accelerators
for research at the frontiers of
knowledge, but there are many
thousands of smaller accelerators.
The following pages highlight
a few of the wide range of
accelerator applications.

Advancing the frontiers of knowledge

In high-energy physics (also called particle physics), particles are accelerated to energies far higher than usually found on earth. Collisions then produce particles that did not exist in nature since the Big Bang, yielding data on the properties of these new particles — fundamental information about nature itself.

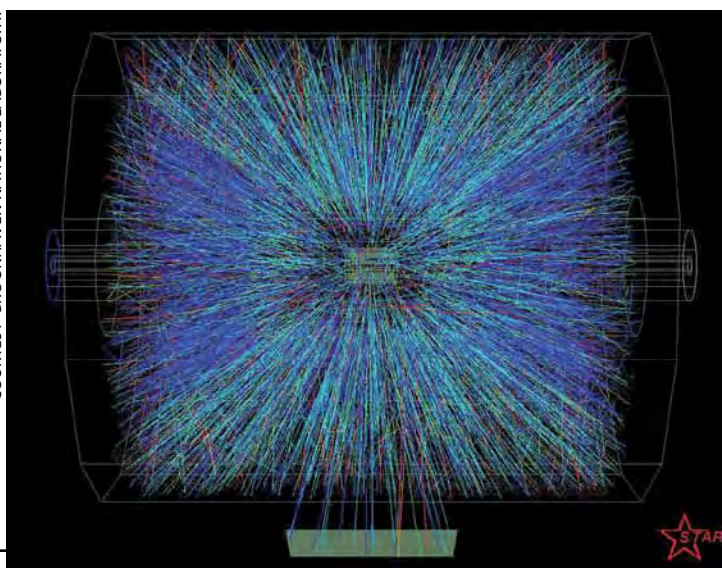
Nuclear physics uses the energy of beams to study the internal properties of the atom's nucleus or the dynamics when nuclei interact. Sometimes this results in producing isotopes that do not normally exist in nature.

Beams for both particle physics and nuclear physics artificially recreate conditions that existed when the universe was much hotter, generating the ambient temperatures from these earlier times.

Such conditions enable pursuit of big questions, such as the meaning of mass, a concept humans have puzzled over for millennia. Why are particles like electrons nearly massless, and particles like protons or top quarks massive?

Some 95% of our universe consists of things we don't understand: dark matter and dark energy. Accelerators offer the possibility of answers.

COURTESY BROOKHAVEN NATIONAL LABORATORY



Collision between gold atoms in the Relativistic Heavy Ion Collider on Long Island. By studying many such collisions, scientists have been able to discover a new state of matter: a quark-gluon plasma.

Accelerators for diagnosing illness and fighting cancer

Across the country and around the world, hospitals and doctors use thousands of medical accelerators.

Cyclotrons, modern versions of the original Lawrence invention, produce many different kinds of radioactive substances, called *isotopes*, for diagnostic procedures and therapy.

Many medical accelerators produce radiation for directly attacking cancer. Advances in proton and ion beam therapy are enabling doctors to avoid harming tissue near the cancer.

RapidArc™ radiotherapy technology by Varian Medical Systems makes it possible to deliver radiation therapy in dramatically shorter treatment times.



COURTESY LOMA LINDA UNIVERSITY MEDICAL CENTER.

The Loma Linda Proton Treatment Center uses a proton synchrotron to accelerate charged positive particles for delivery into the patient's body. This accelerator was constructed at Fermilab.



IMAGE COURTESY OF VARIAN MEDICAL SYSTEMS OF PALO ALTO, CALIFORNIA. ©2009 VARIAN MEDICAL SYSTEMS. ALL RIGHTS RESERVED.

Accelerators to beat food-borne illness

Every week in the United States, about 100 people die from food-borne illness, even though electron accelerators can make food much safer, just as pasteurization makes milk much safer. Electron beams, or X-rays derived from them, can kill dangerous bacteria like *E. coli*, salmonella and listeria.

Food irradiation could join pasteurization, chlorination and immunization as pillars of public health technology. But even though food irradiation is completely safe and does not degrade wholesomeness, nutritional value, quality or taste, consumer acceptance has been slow. That word *irradiation* makes people wary.

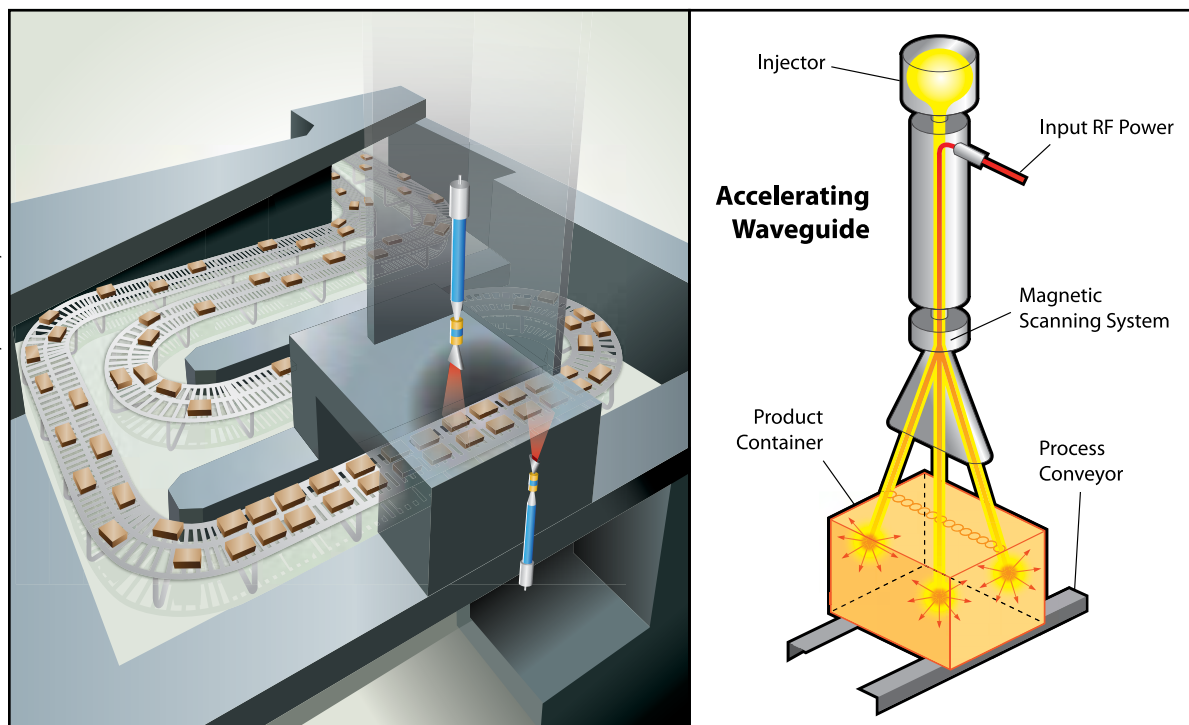
Nevertheless food irradiation increasingly is gaining formal approval in various countries including the United States. Accelerator technology is already making food safer and increasing shelf life, which increases food supply to feed an ever-growing world population and reduce world hunger.



The international Radura symbol indicates food has been irradiated.



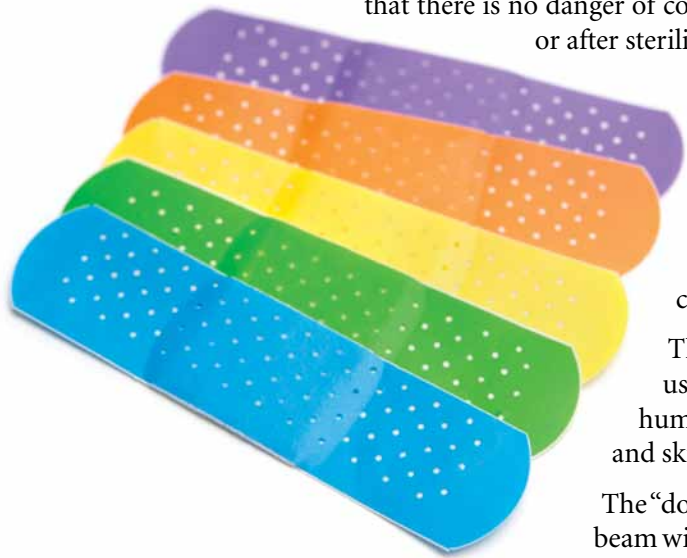
ORIGINAL ILLUSTRATIONS COURTESY SADEX CORP., SIOUX CITY, IOWA.



A production line conveys food products for irradiation by electron beams from two vertical accelerators, one above the conveyor belt and the other below it.

An accelerator makes our band-aids safe

Electron beams can sterilize products effectively, efficiently, and fast. They kill all bacteria. They penetrate packaging, and even the shipping cartons holding the packages, so that there is no danger of contamination during or after sterilization.

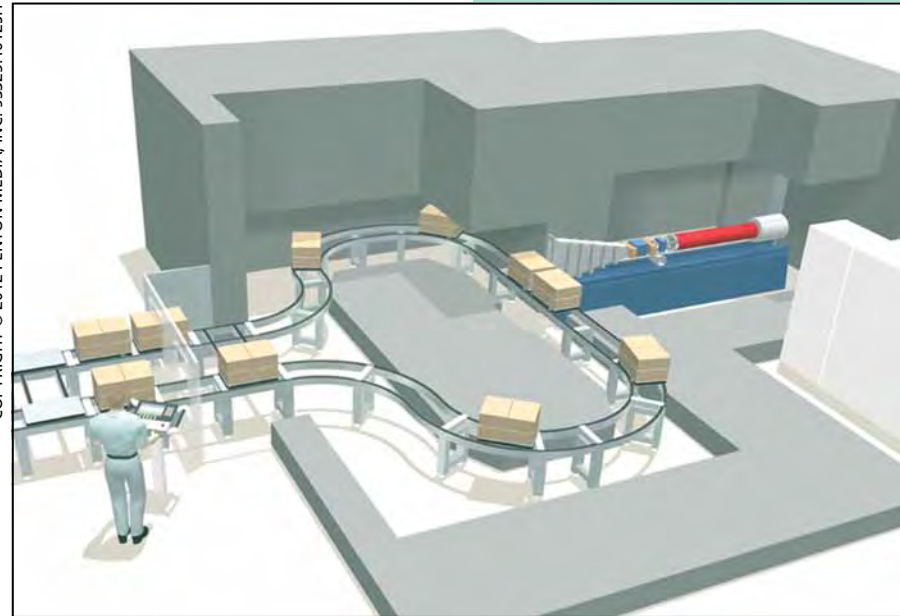


Because the beams generate no heat, they can be used on plastic medical supplies like catheters or cloth bandages.

They can also be used to kill bacteria in human blood platelets and skin grafts.

The “dose” from an electron beam with 10 to 50 kilowatts of power lets the conveyor run as fast as a few feet per minute, allowing sterilization of an entire truckload of boxes in only a few hours. A typical facility can process medical supplies so quickly that it needs several loading docks for offloading and reloading product.

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An electron-beam sterilization facility typically has boxes of product loaded onto a conveyor belt. The boxes pass before the 10 MeV (million electron volts) accelerator. The electron beam sweeps each box, penetrating it and sterilizing its contents. When the boxes reach the conveyor's end, they are piled back onto their pallets. The process moves so fast that it can keep up with a very high volume of product.

COURTESY E-BEAM SERVICES, INC.



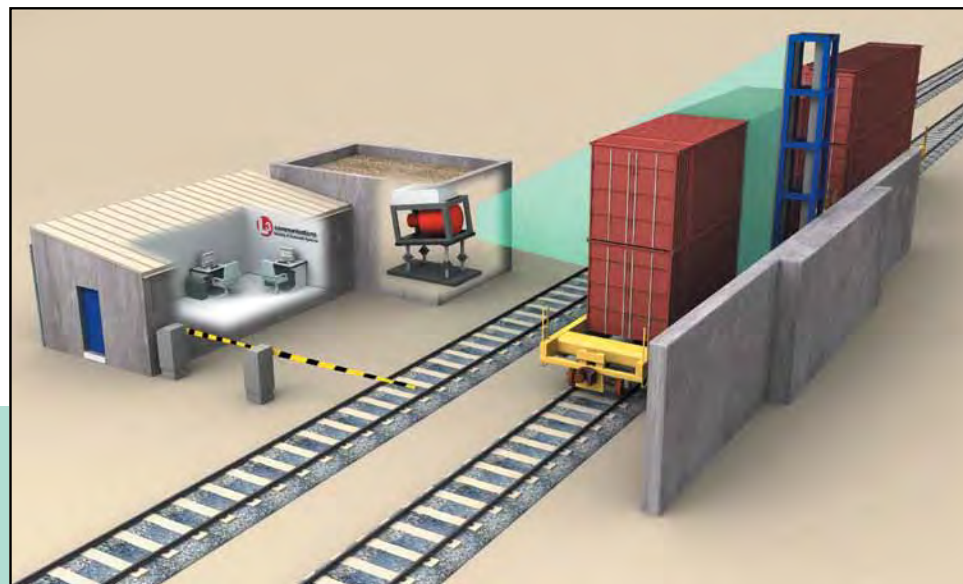
Accelerators and national security

A single ship can bring up to 8000 tractor-trailer-sized cargo containers into an American port. Seven million containers arrive each year. Before distribution around the country, how can these large steel-walled boxes be inspected for what terrorists might have placed into one or some of them? Accelerators offer answers for scanning various kinds of cargo containers and vehicles effectively and efficiently.



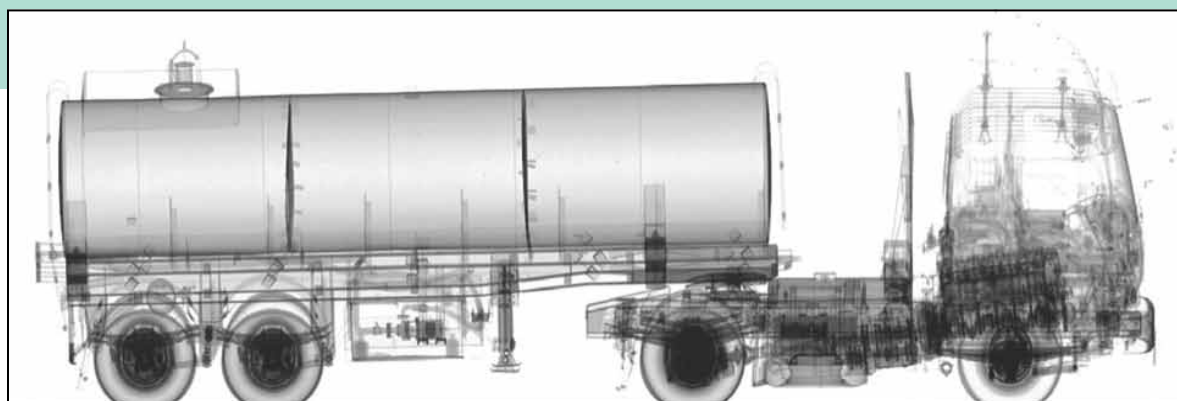
COURTESY RAPISCAN SYSTEMS, CALIFORNIA.

A mobile 6 MeV (million electron volt) X-ray imaging system for versatile inspection of dense cargo.



COURTESY L-3 COMMUNICATIONS SECURITY & DETECTION SYSTEMS.

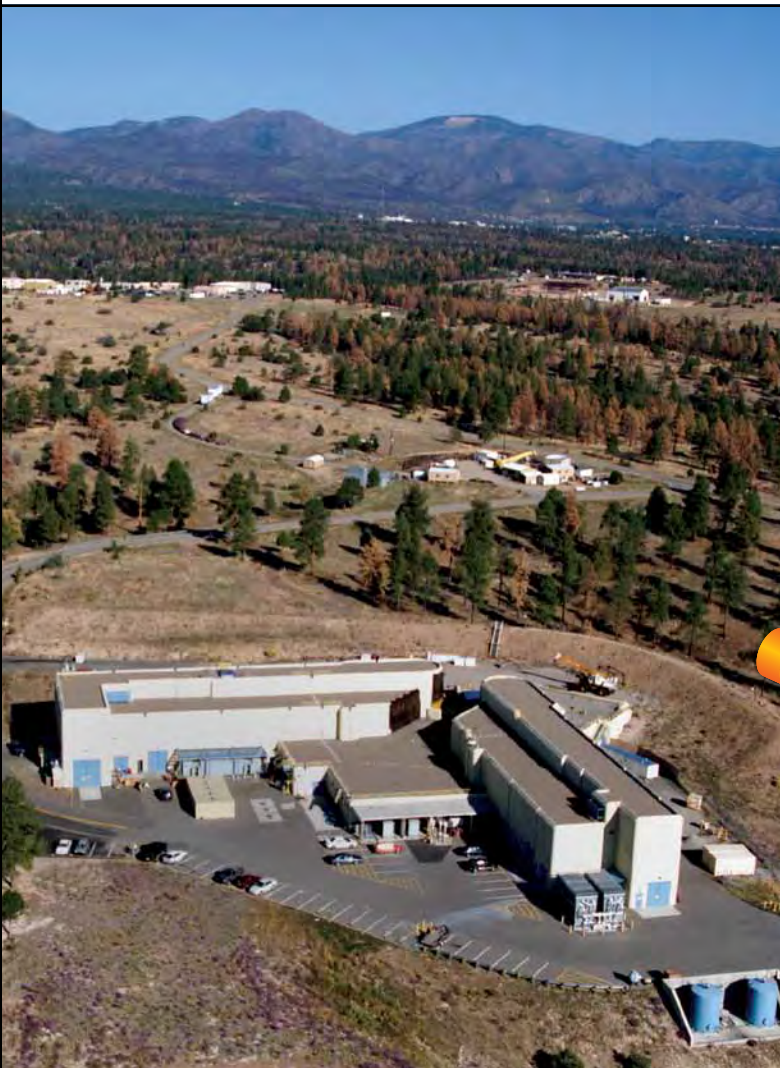
High-density rail cargo imager scans fully loaded trains, tankers and double-stacked cars in a single pass using X-rays.



COURTESY RAPISCAN SYSTEMS, CALIFORNIA.

X-ray image of a truck passing through the inspection portal.

Accelerators validate nuclear weapons readiness



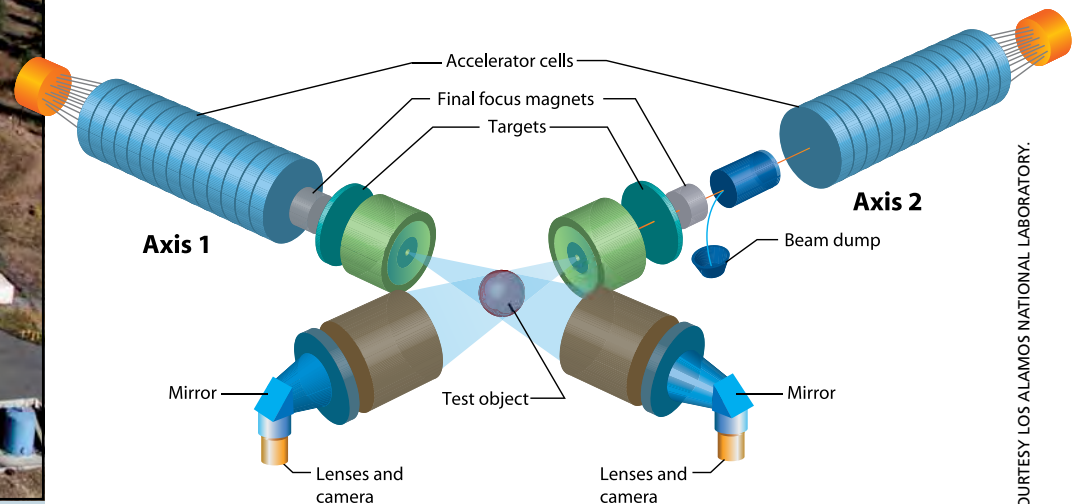
COURTESY LOS ALAMOS NATIONAL LABORATORY.

In a special facility at Los Alamos National Laboratory, two electron accelerators at right angles to each other let scientists monitor realistic but non-nuclear tests of replacement components for the nation's nuclear weapons. "Stockpile stewardship" is necessary because over time some components degrade, perhaps losing functionality, based on interactions from the natural radioactivity of the weapon itself.

Nuclear weapons testing moratoria preclude integrity tests. Therefore non-nuclear tests are necessary. To make the mockup non-nuclear, a heavy metal surrogate stands in for the nuclear fuel, but all other components can be exact replicas.

In the test each electron beam is focused onto a metal target. This target converts the beam's kinetic energy into X-rays that generate images showing the dynamic events that trigger a nuclear detonation. Everything is real except the nuclear fuel.

Because the surrogate fuel and the components being tested become hot enough to melt and flow like water, such a test is called hydrodynamic — leading to the name Dual-Axis Radiographic Hydrodynamic Test Facility, or DARHT Facility.



The DARHT Facility at Los Alamos National Laboratory in New Mexico.

In the DARHT Facility, two electron accelerators work together to enable safe, realistic, non-nuclear monitoring of nuclear weapons readiness.

Beams of light from beams of particles

Light sources for science and technology

Not all light is visible. In science and technology, the word *light* applies generally to electromagnetic radiation. Most wavelengths of light aren't visible. Light sources generate microwave, infrared, visible, ultraviolet, X-ray and gamma-ray light. An equivalent statement is that light sources generate beams of microwave, infrared, visible, ultraviolet, X-ray and gamma-ray photons. (See illustration A.)

How do physicists generate intense, focused light beams from an accelerator? They use magnets, just as they do to steer particle beams through the accelerator. When a particle beam passes between the north and south poles of an accelerator magnet — N and S in illustration B — the beam not only changes direction, it also emits exceptionally intense, tightly focused light. With magnets, physicists not only can steer a particle beam around a circular accelerator or through a linear one, but — as in illustration C — they can tap the accelerator beam to get light beams. This light can then be directed away from the accelerator, shining down beamlines to scientific experiments or technological uses.

Illustration A

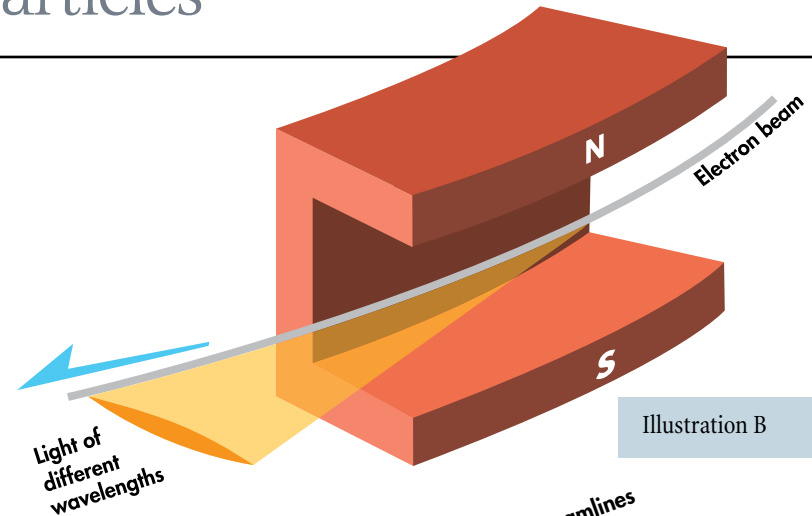
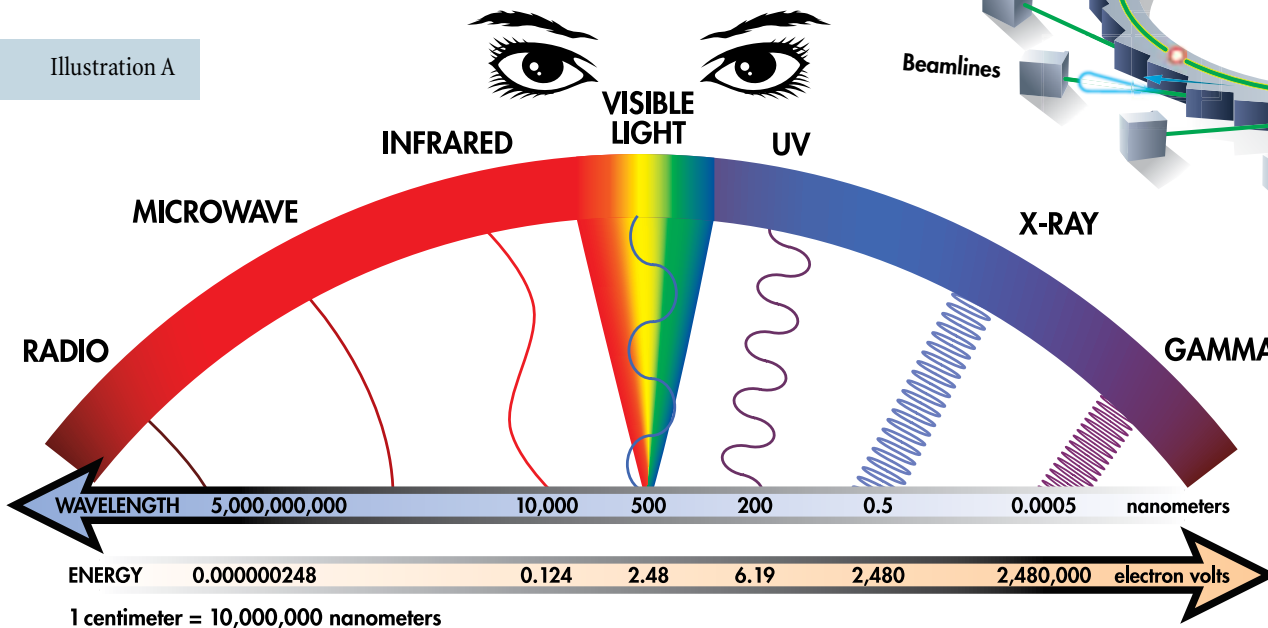


Illustration B

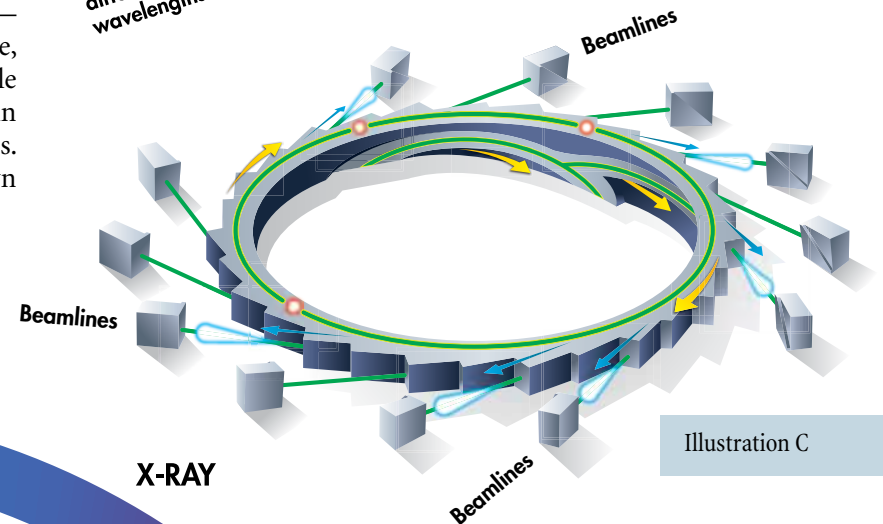
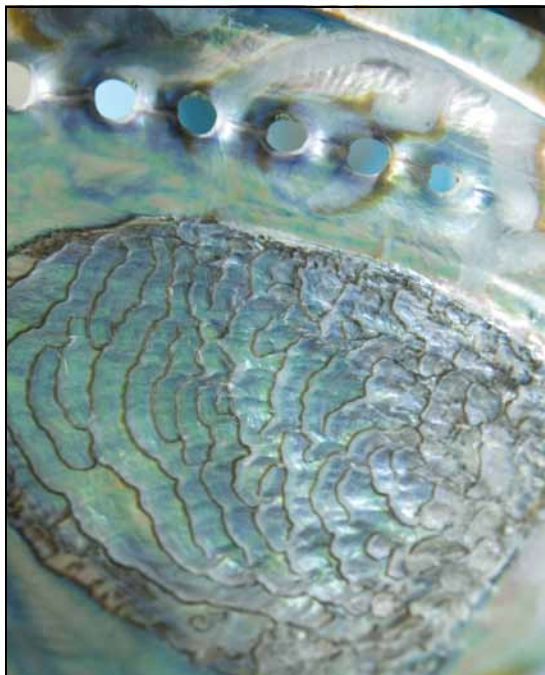


Illustration C

Beams of light from beams of particles

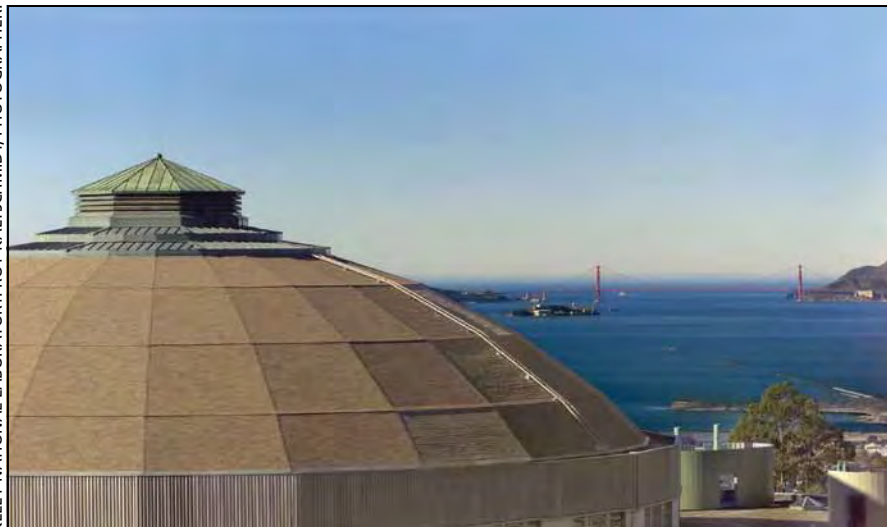
PHOTO JEFF MILLER, UNIVERSITY OF WISCONSIN, MADISON.



Why is the microscale architecture of mother-of-pearl — the iridescent material that lines abalone shells — 3000 times more fracture-resistant than its mineral building blocks? Could human-made materials incorporate that strength and simplicity? Researchers using light sources can investigate questions like these.

At Brookhaven National Laboratory, the National Synchrotron Light Source II will provide extremely bright X-rays for basic and applied research in biology and medicine, materials and chemical sciences, geosciences and environmental sciences, and nanoscience.

COURTESY LAWRENCE BERKELEY NATIONAL LABORATORY. ROY KALTSCHMIDT, PHOTOGRAPHER.

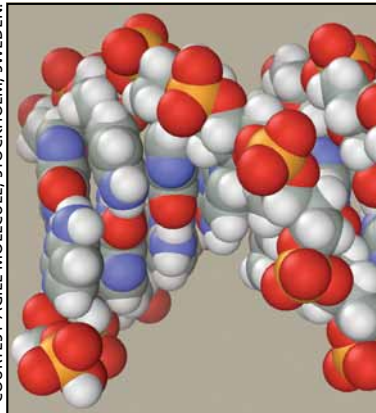


At the Advanced Light Source (ALS) at Lawrence Berkeley National Laboratory, the light is so bright, and can be so finely tuned to specific wavelengths, that it reveals precise details about the arrangement and behavior of atoms and electrons in complex materials.

Researchers use the light to detect the origin of air pollutants, identify the components of comet dust, examine the nanoscale pores of multi-use aerogels, observe electrons as they flip and spin on magnetic disks, and catch proteins in the act of folding and unfolding.

Every year thousands of biologists, chemists, materials scientists, climatologists, medical researchers, and physicists come to the ALS to use it for experiments. Even operating around the clock, the ALS can only accommodate about half of its user demand.

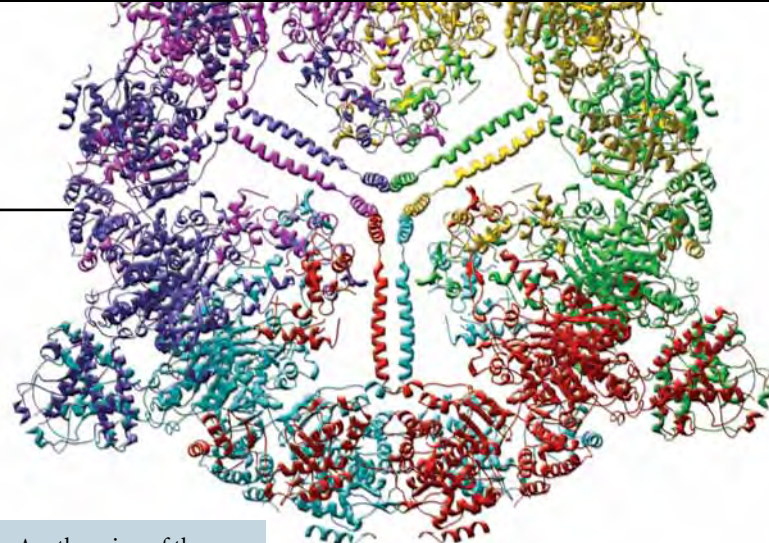
COURTESY AGILE MOLECULE, STOCKHOLM, SWEDEN.



COURTESY NATIONAL SYNCHROTRON LIGHT SOURCE,
BROOKHAVEN NATIONAL LABORATORY.

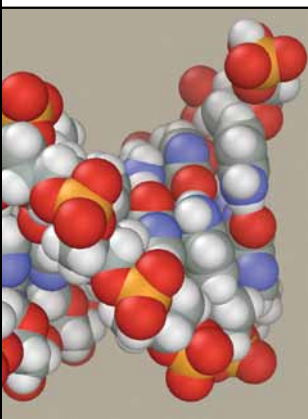


Representative of the molecular structure of an HIV gp120 (red) envelope glycoprotein in complex with the CD4 (yellow) receptor and a neutralizing human antibody. The structure was determined by Wayne Hendrickson's group (Columbia University) at beamline X4A, National Synchrotron Light Source.



Another view of the yeast enzyme described in more detail below.

COURTESY I. LOMAKIN, Y. XIONG, T. A. STEITZ, YALE UNIVERSITY.

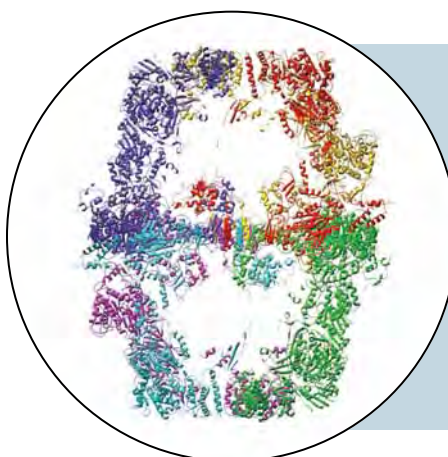


THE SCALE FOR THESE SCIENTIFIC REPRODUCTIONS IS THE ORDER OF A FEW NANOMETERS (1 BILLIONTH OF A METER).

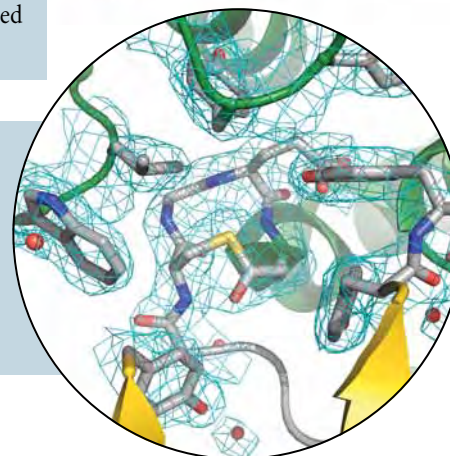
At Argonne National Laboratory scientists use the brilliant beam from the Advanced Photon Source to reveal how proteins function. The Human Genome project identified 20,000 to 25,000 genes in human DNA that regulate everything from breathing to digestion and sweating. Understanding how DNA generates and regulates proteins can help prevent or cure diseases in humans.

The figure shows a computer-generated model of a DNA fragment.

COURTESY I. LOMAKIN, Y. XIONG, T. A. STEITZ, YALE UNIVERSITY.



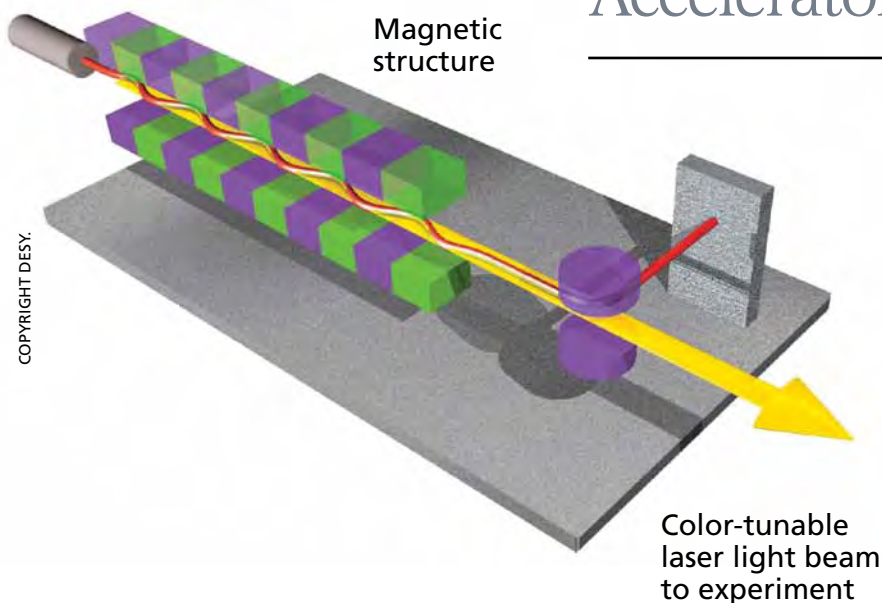
Using the Advanced Photon Source, researchers from the University of Texas Southwestern Medical Center believe they can contribute to the fight against malaria, a disease that kills millions. They study how a protein in mosquito immune systems operates against the parasite that causes malaria.



THANKS TO PRICHARD BAXTER AND JOHANN DEISENHOFER FOR PROVIDING THE IMAGE.

Enzymes are essential molecules, working hard to catalyze and direct cellular reactions, and, incredibly, making it all look effortless. The more science learns about enzyme complexes, the more awe these wonder proteins seem to merit. A research team from Yale University used beamlines at light sources at Argonne, Cornell and Brookhaven to glean important information about the yeast enzyme's structure and function, imaged here. The researchers unveiled the breathtaking complexity of this enzyme that synthesizes fatty acids, and made important progress in understanding how it works and how it can lead to disease when it malfunctions.

Electron accelerator



Accelerators energize a new kind of laser

Making laser light from electron beams

Conventional lasers make their extraordinarily useful kind of light by jiggling electrons that are bound in atoms. Accelerator-driven free-electron lasers (FELs, pronounced as three separate letters) make light by using magnets to jiggle electrons that are freed from atoms, as shown at the left. With free electrons, the light's wavelength (color) can be selected. For many applications, that's a very important feature.

Magnets in an FEL jiggle the free electrons in a beam from an accelerator. Operators can select the resulting light's wavelength by varying the beam's energy or the magnetic field strength.

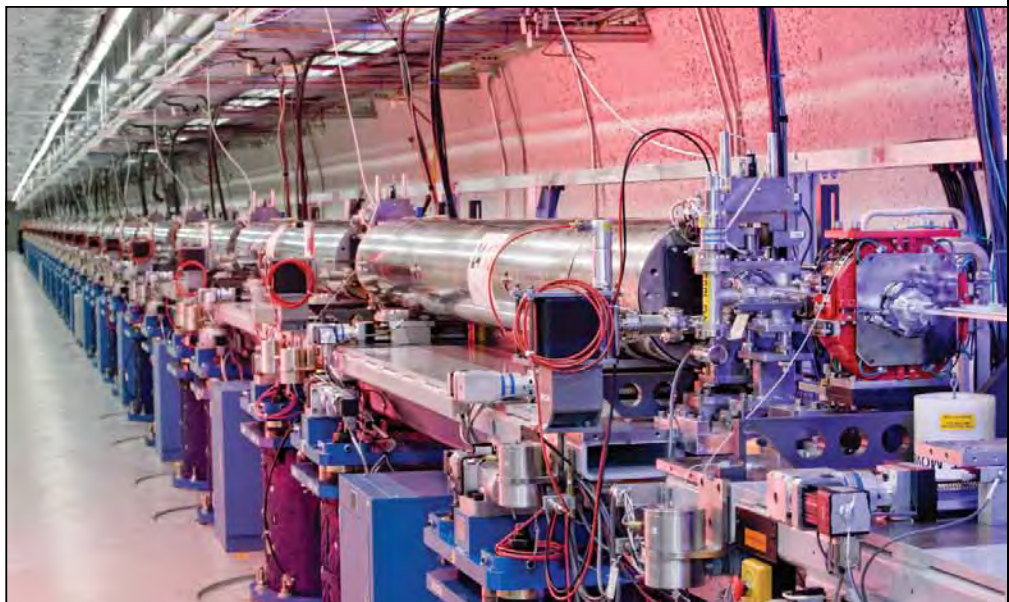
An FEL's beam is delivered in pulses rather than a steady stream. These bursts of light can be timed, with pulse sequences shorter than a trillionth of a second. For many applications, this too is a very important feature.

Powerful X-ray laser light from electron beams

At Stanford University's SLAC National Accelerator Laboratory, the Linac Coherent Light Source (LCLS), shown at the right, is the world's most powerful X-ray laser. The linac (linear accelerator) generates high-energy beams of free electrons for making this special kind of light.

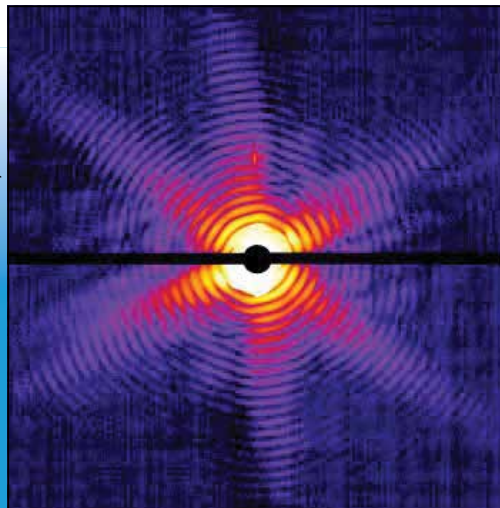
The resulting laser light arrives in staccato bursts one-tenth of a trillionth of a second long. These intense, ultrafast pulses let researchers scrutinize complex, ultrasmall structures by freeze-framing atomic motions. The researchers get to see the fundamental processes of chemistry, drug development and life itself in a new light.

COURTESY SLAC



Free-electron laser applications

IMAGE COURTESY TOMAS EKEBERG, UPPSALA UNIVERSITY.



The first single-shot images of intact viruses pave the way for snapshots and movies of molecules, viruses and live microbes in action.

Capturing this image demonstrates the unique capabilities of the world's most powerful X-ray FEL, showing how it could revolutionize the study of life. The X-ray pulse lasted a millionth of a billionth of a second and heated the virus to 100,000 degrees.

X-ray diffraction pattern of a single mimivirus particle imaged at the Linac Coherent Light Source.



Speed of sound

Speed of light

At Los Alamos National Laboratory in New Mexico, researchers are developing high-power FELs for defending ships from cruise missile attacks. The US Office of Naval Research sponsors the work. An onboard FEL's output wavelength can be changed to match varying atmospheric conditions. At the right wavelength, the laser beam can travel a long distance and still deliver the necessary destructive power.

A free-electron laser (FEL) could provide speed-of-light defense against a speed-of-sound attack.



Accelerators for improving materials' surfaces

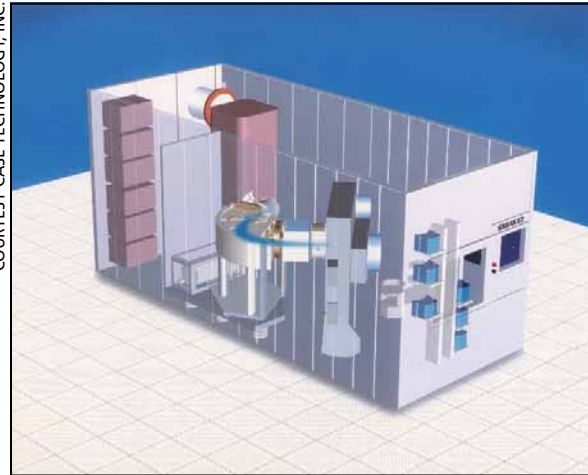
An accelerator-based manufacturing technique called ion implantation modifies semiconductors' electrical properties precisely and cost-effectively, leading to better, cheaper electronics.

Ions are atoms with positive or negative charge. Implanting them very precisely in metal surfaces means greater toughness. In tools like drill bits, that means a longer working lifetime.

Ion implantation also means less corrosion. Greater toughness and less corrosion mean medical prostheses like artificial hips last longer.

Chip manufacturers create integrated circuits by intentionally introducing impurities — boron or phosphorus ions — into silicon wafers. Using an accelerator they create a beam of high-energy boron or phosphorus ions, and then move the silicon wafers into the beam for implantation of the ions into the wafers.

COURTESY CASE TECHNOLOGY, INC.



A typical ion implanter.

COURTESY OAK RIDGE NATIONAL LABORATORY.



Nitrogen ions implanted into surgical alloys — as in this artificial femur — reduce wear and corrosion from body fluids, freeing patients from the need for repeated surgery.



Accelerator-based neutron science yields payoffs



COURTESY OAK RIDGE NATIONAL LABORATORY.

The accelerator-based Spallation Neutron Source in Oak Ridge, Tennessee, produces the world's most intense pulsed neutron beams for research and industrial development. Six US Department of Energy laboratories worked together to build it.

Only negatively or positively charged particles can be accelerated. But accelerated particle beams can cause the release of neutrons. In turn, these electrically neutral particles can be formed into beams themselves, yielding practical payoffs.

The uncharged neutrons can go where charged particles can't, providing detailed snapshots of material structure and "movies" of molecules in motion. This neutron research improves a multitude of products, from medicine and food to electronics, cars, airplanes and bridges.

One particularly tantalizing neutron-research subject is superconductors, materials that conduct electricity with almost no energy loss. Neutron research shows how electromagnetic fields behave inside certain superconductors.

If superconductors can be developed for the electrical grid, a hydroelectric dam or a wind farm could provide cheaper power to distant cities.



Future high-speed trains, possibly levitated by superconducting magnets, will be even faster than Shanghai's maglev train.

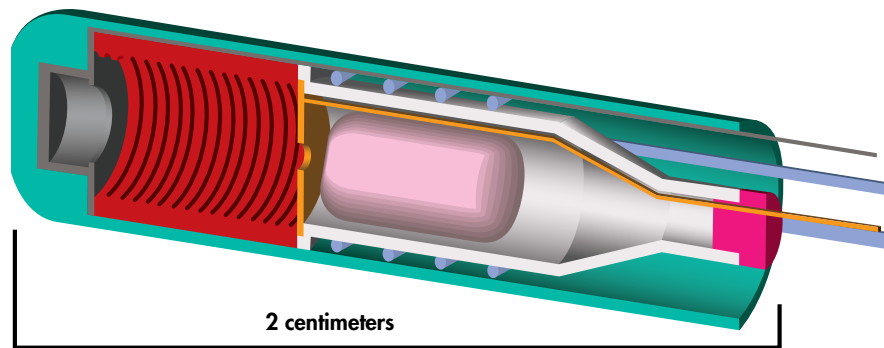
PHOTO ALEX NEEDHAM (WIKIPEDIA).

Multiple uses for portable accelerators

Attach certain instruments to a compact, vacuum-tight accelerator called a portable neutron generator, lower it down a borehole, and you can look for oil.

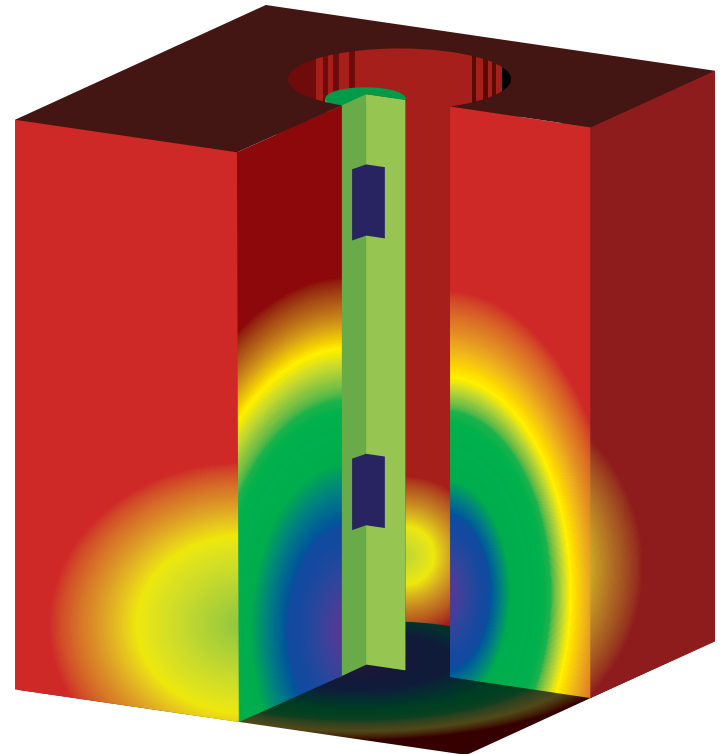
The accelerator generates the neutrons by manipulating isotopes of hydrogen. It can discover oil deposits by detecting porosity, which shows the presence of liquid or gas. Electrical characteristics tell whether a liquid is water or oil.

Portable neutron generators have other uses too. They can analyze metals and alloys, and they can detect explosives, drugs, or materials for nuclear weapons.



A small deuteron-triton accelerator, a “mini-neutron tube,” is used for oil well analysis during drilling, as well as homeland security detection of explosives and fissile materials in luggage or cargo.

FROM AN IMAGE BY KA-NGO LEUNG,
LAWRENCE BERKELEY NATIONAL LABORATORY TECHNOLOGY TRANSFER.



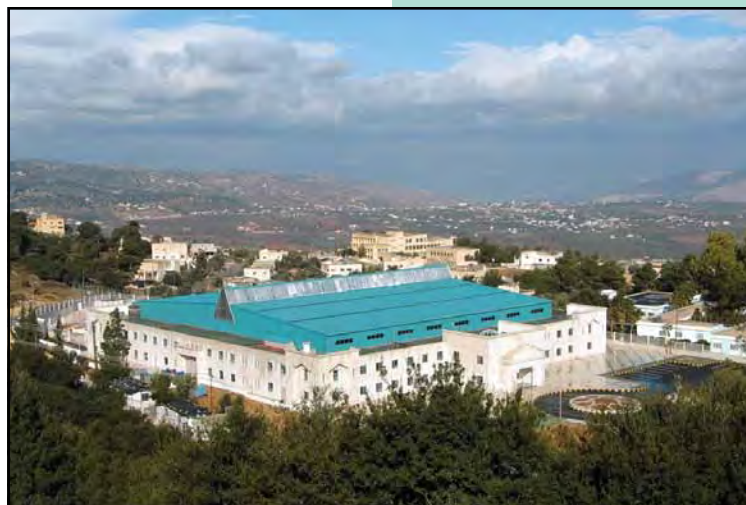
FROM AN IMAGE BY
LAWRENCE LIVERMORE NATIONAL LABORATORY.

Computer simulation of oil well analysis using a small deuteron-triton accelerator.

Accelerators boost international cooperation

CERN, the prestigious European Organization for Nuclear Research, and Fermilab, each with a long tradition of international cooperation, serve researchers who work cooperatively and represent scores of nations. These and many other accelerator laboratories link diverse societies and contribute to a culture of peace. Builders and users of accelerators and accelerator-driven light sources come together regularly at international conferences.

SESAME (Synchrotron-light for Experimental Science and Applications in the Middle East), a synchrotron light source under construction in Jordan, set up under the auspices of UNESCO, is closely modeled on CERN. Note the remarkable membership list: Bahrain, Cyprus, Egypt, Iran, Israel, Jordan, Pakistan, the Palestinian Authority and Turkey. This advanced synchrotron will serve a wide spectrum of disciplines, ranging from biology and medical sciences through materials science, physics and chemistry to archeology.



The SESAME site and building.



The microtron, first link in the accelerator chain, is now installed and operating at SESAME at its full energy of 22 MeV (million electron volts). It is a refurbished and upgraded part of a decommissioned facility donated by Germany, as is the booster ring, which is expected to be installed and operating at full energy (800 MeV) soon. The booster will inject electrons into a completely new, much larger 2.5 GeV (billion electron volts) storage ring.

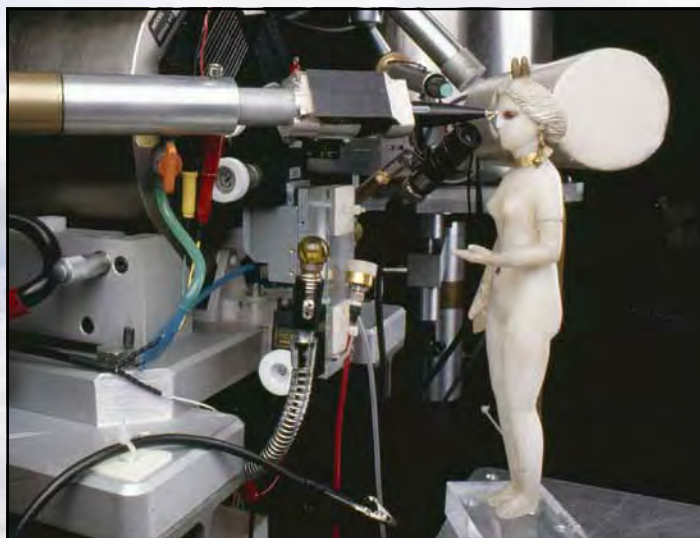
PHOTO COURTESY RAFFIK SARRAF (SESAME).

PHOTO COURTESY MACIEJ NALECZ (UNESCO).



Why is an accelerator under the Louvre museum?

AGLAE, Accélérateur Grand Louvre d'Analyse Élémentaire in Paris, is the world's only accelerator facility fully dedicated to the study and investigation of works of art and archeological artifacts. It serves more than 1200 French museums. The 4-million-electron-volt proton beam delicately probes a large variety of materials: jewels, ceramics, glass, alloys, coins and statues, as well as paintings and drawings. These investigations provide information on the sources of the materials, the ancient formulas used to produce them, and the optimal ways to preserve these treasures.



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The Story of Ishtar

In 1863, while excavating a tomb from the ancient Parthian civilization in Mesopotamia (200 BC – 200 AD), an amateur archeologist who was the French consul in Baghdad discovered this 5-inch-tall alabaster figurine representing the goddess Ishtar. He donated it to the Louvre. Recently a Louvre curator asked the AGLAE team to analyze the figurine's red eyes and red navel. The inlays turned out to be exquisite rubies, a great mystery since rubies are only found in remote lands like India or Southeast Asia. Analysis of rubies with known provenance from Paris jewelers yielded trace-element fingerprints showing that Ishtar's rubies originated in Burma — testifying to an unreported trade network (see map), perhaps by ship, between Babylon and Southeast Asia.



MAP BY T. CALLIGARO.

PHOTO BY OLIVIA DIAZ.

Accelerators and astronomy

Accelerators are like microscopes. Microscopes reveal what's extremely small. Accelerators reveal information about what's millions of times smaller still.

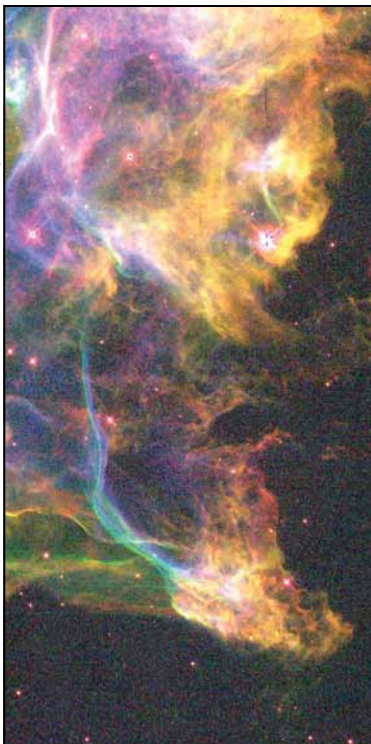
Accelerators are also like telescopes. Telescopes reveal the universe itself. Accelerators reveal information that helps astronomy.

Accelerators are used to study nuclear processes that first occurred during the Big Bang and that continue in stars, novae and supernovae. This field is called **nuclear astrophysics**.

Accelerator physicists work with nuclear astrophysicists to use high-intensity, low-energy beams to explore reactions at stellar energies.

The Facility for Rare Isotope Beams, under construction at Michigan State University, will provide intense beams of rare isotopes, short-lived atomic nuclei not normally found on earth. This facility will enable researchers to address questions such as: What is the origin of the elements we find in nature? Why do stars sometimes explode?

COURTESY NASA, HUBBLE TELESCOPE



A small portion of a supernova remnant from about 15,000 years ago.

COURTESY NASA, HUBBLE TELESCOPE



Observations of a pair of star clusters 166,000 light years away suggest they might be linked through stellar evolution processes.

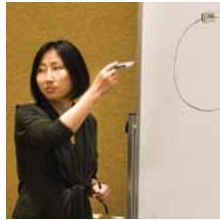
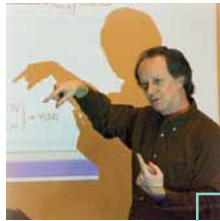
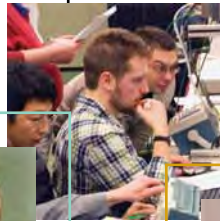
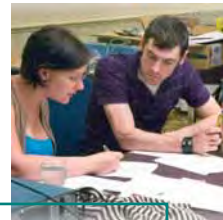
Education

As accelerator science and technology have advanced, the use of accelerators has grown explosively. Accelerators are crucial to medicine and to the semiconductor industry and are likely to become even more central to many fields of research. We need to continue to educate accelerator scientists and support accelerator research centers. This field is one of the most effective for educating students who can then work productively in many fields and industries.

The US Particle Accelerator School (USPAS) is a unique institution funded by the US Department of Energy and a consortium of national laboratories. Each year, it holds two sessions hosted by major research universities. At each two-week session, about 130 students participate in one of a dozen for-credit courses.

The role and responsibility of the USPAS will grow over the next decade, as challenging new colliders, light sources, and laser-driven accelerators come into operation. The next decade promises the construction of a Facility for Rare Isotope Beams (FRIB), an upgrade for the Large Hadron Collider, and possibly the construction of the International Linear Collider or an accelerator-driven neutrino source. US accelerator-based science must have access to sufficient scientific and engineering talent with a broad array of technical skills. To meet this challenge, the USPAS must train more early-career scientists and engineers than ever.

FACULTY AND STUDENT COLLAGES
COURTESY WILLIAM BARLETTA, DIRECTOR,
US PARTICLE ACCELERATOR SCHOOL.



Jobs designing, constructing, operating and maintaining accelerators



COURTESY FERMILAB.

Accelerators bring high-tech jobs. More than 30,000 accelerators worldwide serve an expanding variety of fields — and more than 65 manufacturers are shipping almost a thousand new systems each year. To design, build, operate and maintain these accelerators requires workers with an enormous variety of scientific, engineering, technological, medical and industrial skills. Some market statistics indicate the annual breadth and reach of the high-tech career opportunities involved. The financial size of the accelerator industry is a measure of the many job opportunities there are:

- Industrial electron-beam irradiation generates \$90 billion
- Semiconductor components from ion implantation exceed \$250 billion
- Goods with materials and parts touched by accelerators yield more than a half-trillion dollars

Accelerator operation



COURTESY CURTIS ALLEN, ALTAR TECHNOLOGIES, INC.

Accelerator construction

Outreach

Accelerator laboratories seek to make science accessible to school children and adults and to train young scientists for accelerator careers. Here are a few examples:

Jefferson Laboratory in Virginia initiated BEAMS — Becoming Enthusiastic About Math and Science — so that middle school students and their teachers could visit for an engaging week of activities with scientists, engineers and technicians.

Michigan State University graduate students in beam physics initiated Science Theatre — informal shows and demonstrations — to interest and inform the public concerning scientific phenomena.

Fermilab is committed to enhancing mathematics and science education and stimulating science literacy. Programs engage students of all ages, reach out to the general public, promote improvement in education, and serve as a resource for schools and districts nationwide.

Future accelerator physicists receive hands-on experience at France's National Institute for Nuclear Science and Technology (INSTN) at the Saclay laboratory. The INSTN is entirely devoted to accelerator and ion-beam analysis teaching.



PHOTOS COURTESY OF
(TOP LEFT) JEFFERSON LABORATORY
(TOP RIGHT) FERMILAB
(MIDDLE LEFT) MICHIGAN STATE UNIVERSITY
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(BOTTOM LEFT) JEFFERSON LABORATORY.

Looking to the future

Accelerators significantly affect the economy, health, and security in the US and in many other countries. Accelerator scientists and engineers are continuously at work to find ways to make accelerators cheaper, easier to operate and more reliable and compact.

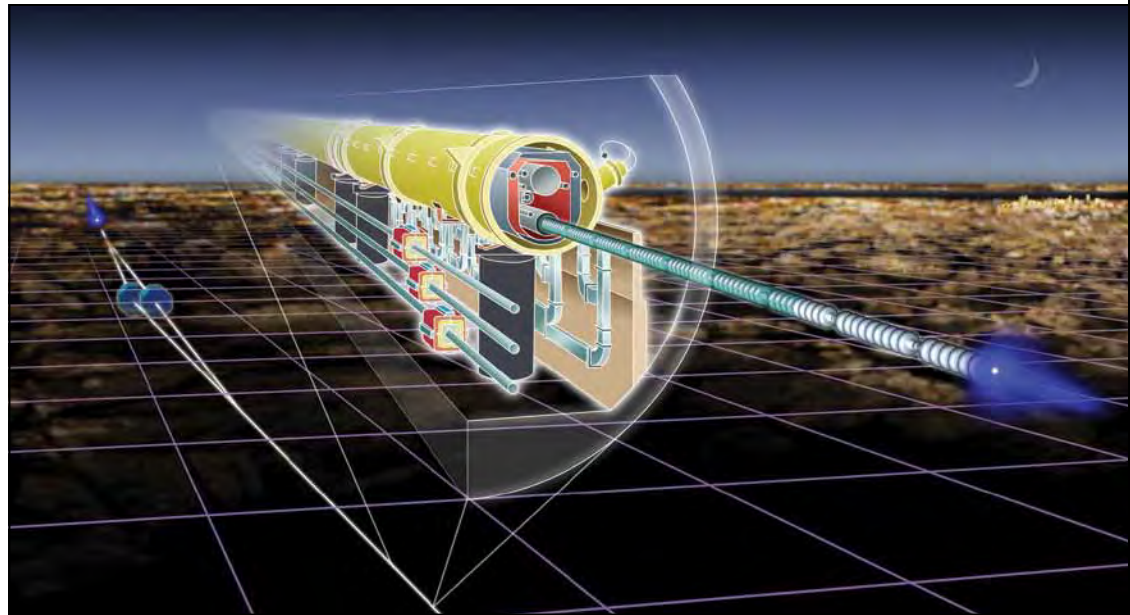
At the highest-energy frontier of physics, Europe's Large Hadron Collider (LHC) is delivering exciting new findings. For the past half-century, such facilities have yielded remarkable discoveries of previously undetected quarks and bosons.

These discoveries have been followed by intensive investigations at electron-positron colliders, where collisions between electrons and their antimatter opposites yield results that build on the findings. The International Linear Collider has been proposed as the next major electron-positron machine.

The other main thrust in particle physics is the study of neutrinos — elusive particles that lack charge. Promising concepts are a storage-ring-type accelerator for muons, which can be thought of as heavy electrons.

And indeed physicists, including accelerator builders, are always looking ahead. It seems inevitable that even beyond LHC's extraordinarily high energies, nature will still present secrets to unravel. That's why physicists believe that studies of the possibilities for future generations of colliders should be sustained, extending work carried out at Fermilab and the LHC.

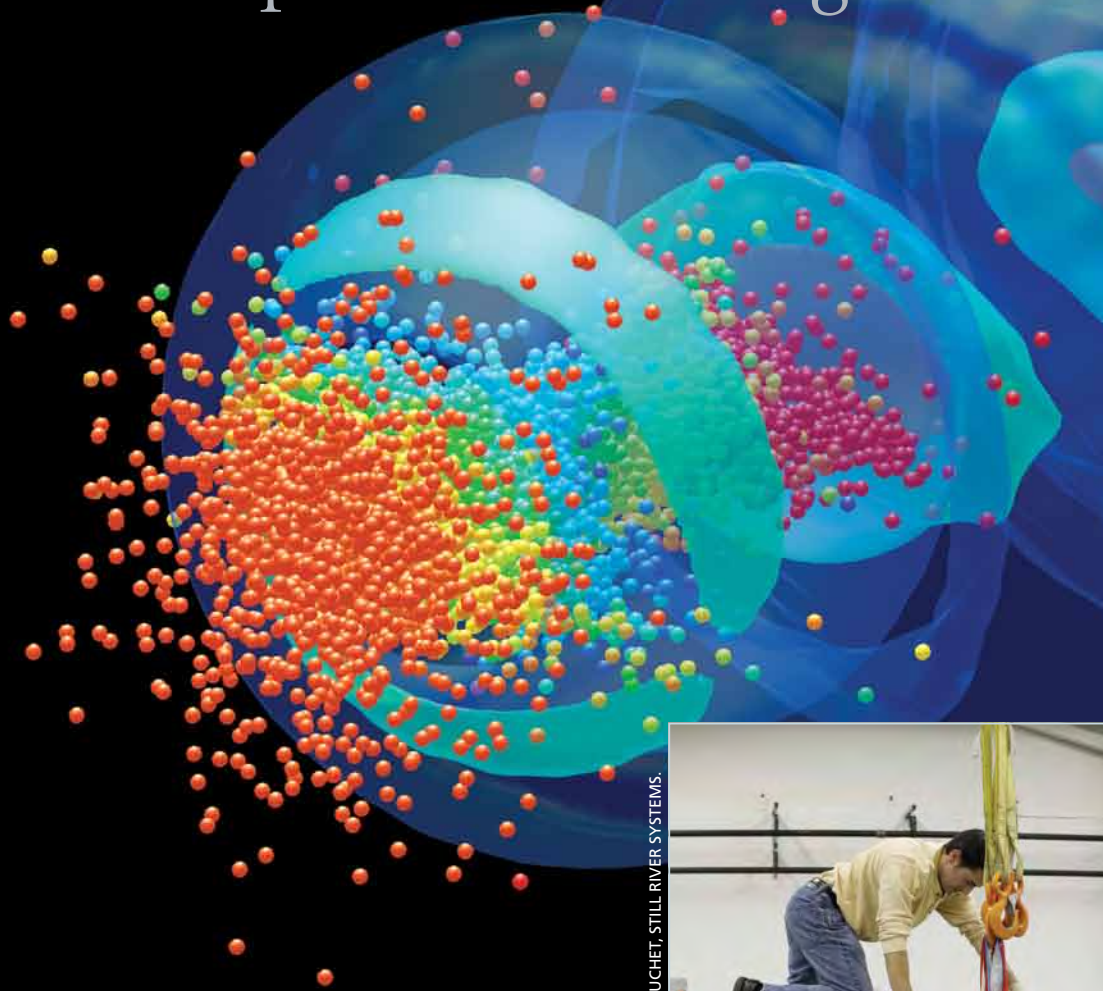
A major challenge for the accelerator science community is to identify and develop new concepts for future frontier accelerators that will constitute the exploration tools needed for discovery physics within a feasible cost to society.



COURTESY SLAC.

The International Linear Collider's two linear accelerators will hurl electrons and their antiparticles, positrons, toward each other at nearly the speed of light. Superconducting accelerator cavities operating at temperatures near absolute zero will give the particles more and more energy until they collide at the center. The machine will stretch approximately 31 kilometers. The beams will collide 14,000 times every second at the extremely high energy of 500 billion electron volts (GeV).

Developing new accelerator concepts and technologies



Simulation of a Stanford investigation of a promising technique called plasma-wakefield acceleration.

COURTESY LIONEL BOUCHET, STILL RIVER SYSTEMS.



Table-sized superconducting cyclotron for single-room proton-radiation treatment.



Full-scale model of the radio-frequency cavity of a superconducting cyclotron design of the AIMA Company for high-energy proton therapy.

COURTESY ACCELERATORS FOR INDUSTRIAL AND MEDICAL APPLICATIONS.

IMAGE CREDIT: F TSUNG, UCLA.

Could accelerators revolutionize nuclear energy?

Physicists have long envisioned a new method to produce nuclear power: accelerator-driven subcritical reactors, or ADSs, to generate electricity cleanly, safely, and cheaply.

ADS-generated electricity would come without greenhouse gases, without byproducts useful to terrorists, and with minimal nuclear waste.

An ADS could also transmute radioactive wastes from conventional nuclear power stations to generate power while making disposal safer and cheaper.

Since it's easy to switch off an accelerator, an ADS would inherently preclude any possibility of a runaway nuclear reaction.

In a conventional reactor, a chain reaction produces the copious neutrons needed for fission. In an ADS, proton beams from an accelerator would produce them.

In some countries, their abundant element thorium could provide fuel for an ADS.

The ADS vision has required accelerators to evolve, and they have done so. Now researchers worldwide are investigating how to amplify an accelerator's energy many times.

Conclusion

From pure research to practical applications

Most of what we know and can learn about the fundamental nature of matter comes from probing it with directed beams of particles: electrons, protons, neutrons, heavy ions, and photons. The resulting ability to “see” the building blocks of matter has had an immense impact on society and our standard of living.

Over the last century, particle accelerators have changed the way we look at nature and the universe we live in, and have become integral to the nation’s technical infrastructure. Particle accelerators are essential tools of modern science and technology.

A beam of the right particles with the right energy at the right intensity can shrink a tumor, produce cleaner energy, spot suspicious cargo, make a better radial tire, clean up dirty drinking water, map a protein, study a nuclear explosion, design a new drug, make a heat-resistant automotive cable, diagnose a disease, reduce nuclear waste, detect an art forgery, implant ions in a semiconductor, prospect for oil, date an archaeological find, package a Thanksgiving turkey or discover the secrets of the universe.

– Judy Jackson, Fermilab



COURTESY OF NORDION AND ADVANCED CYCLOTRON SYSTEMS, INC.

Nordion’s three cyclotrons located at the TRIUMF Laboratory in Canada, including this TR30, produce enough isotopes for 2.5 million patient procedures per year.



COURTESY OF IBA, ION BEAM APPLICATIONS, HEADQUARTERED IN BELGIUM.

IBA’s 230-MeV (million electron volts) cyclotron is used for proton therapy in 14 hospitals worldwide.

To learn more



Dimensions of Particle Physics,
a joint Fermilab/SLAC publication
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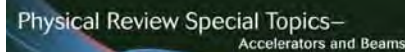


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