



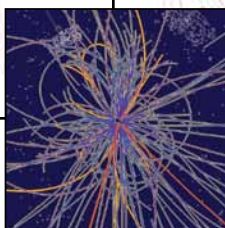
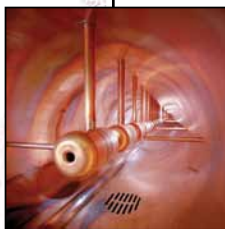
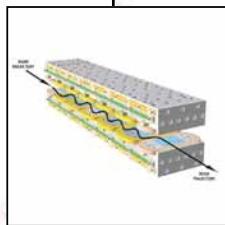
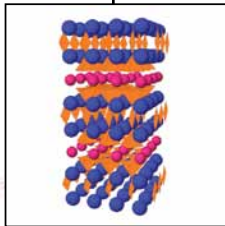
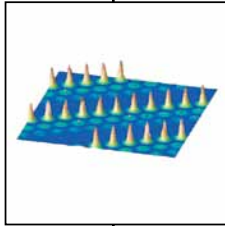
# Accelerators AND Beams

TOOLS OF DISCOVERY AND INNOVATION

Published by the Division of Physics of Beams of the American Physical Society



# Accelerators AND Beams



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PHOTOS TOP TO BOTTOM: (1) INVESTIGATION OF MAGNETISM IN NANOWIRES WITH A HIGH-ENERGY LIGHT SOURCE. (2) ATOMIC MODEL OF YTTRIUM-BARIUM-COPPER OXIDE, A HIGH-TEMPERATURE SUPERCONDUCTING CERAMIC WHOSE OXYGEN POSITIONS WERE DETERMINED BY NEUTRON SCATTERING. (3) CORNELL UNIVERSITY DESIGN OF A NEW TYPE OF SUPERCONDUCTING WIGGLER TO PRODUCE AN INTENSE X-RAY BEAM. (4) DRIFT TUBES IN THE FERMILAB LINEAR ACCELERATOR. (5) SIMULATION OF DETECTION OF A HIGGS BOSON IN AN EXPERIMENT AT CERN'S LARGE HADRON COLLIDER.

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 is the site of many advances in the dynamic, evolving field of high-energy physics, which probes the tiniest sub-microscopic realms.

Research using beams from particle accelerators has told us almost everything 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 shortly after the Big Bang. Such accelerators unravel nature's deepest mysteries. They are central to 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 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.



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 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 get state-of-the-art cancer therapy from an accelerator.



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 machine 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, in medical applications, and by industry.

There are two families of accelerators.

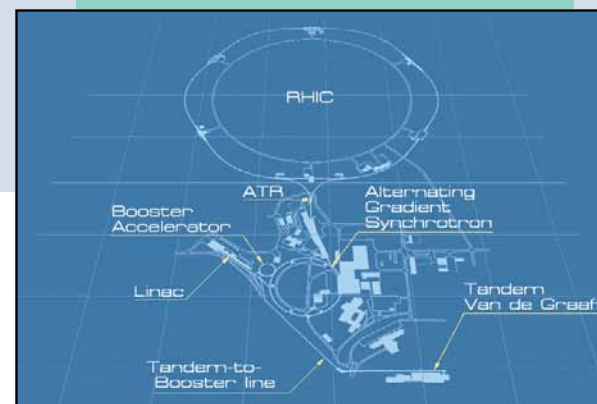
In **linear** accelerators, the beam passes through the accelerating fields and magnetic focusing fields only once.

In **circular** accelerators (cyclotrons and synchrotrons), magnetic fields bend the path of the particles so multiple passes are made 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.)



COURTESY BROOKHAVEN NATIONAL LABORATORY.

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.

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

# The invention of

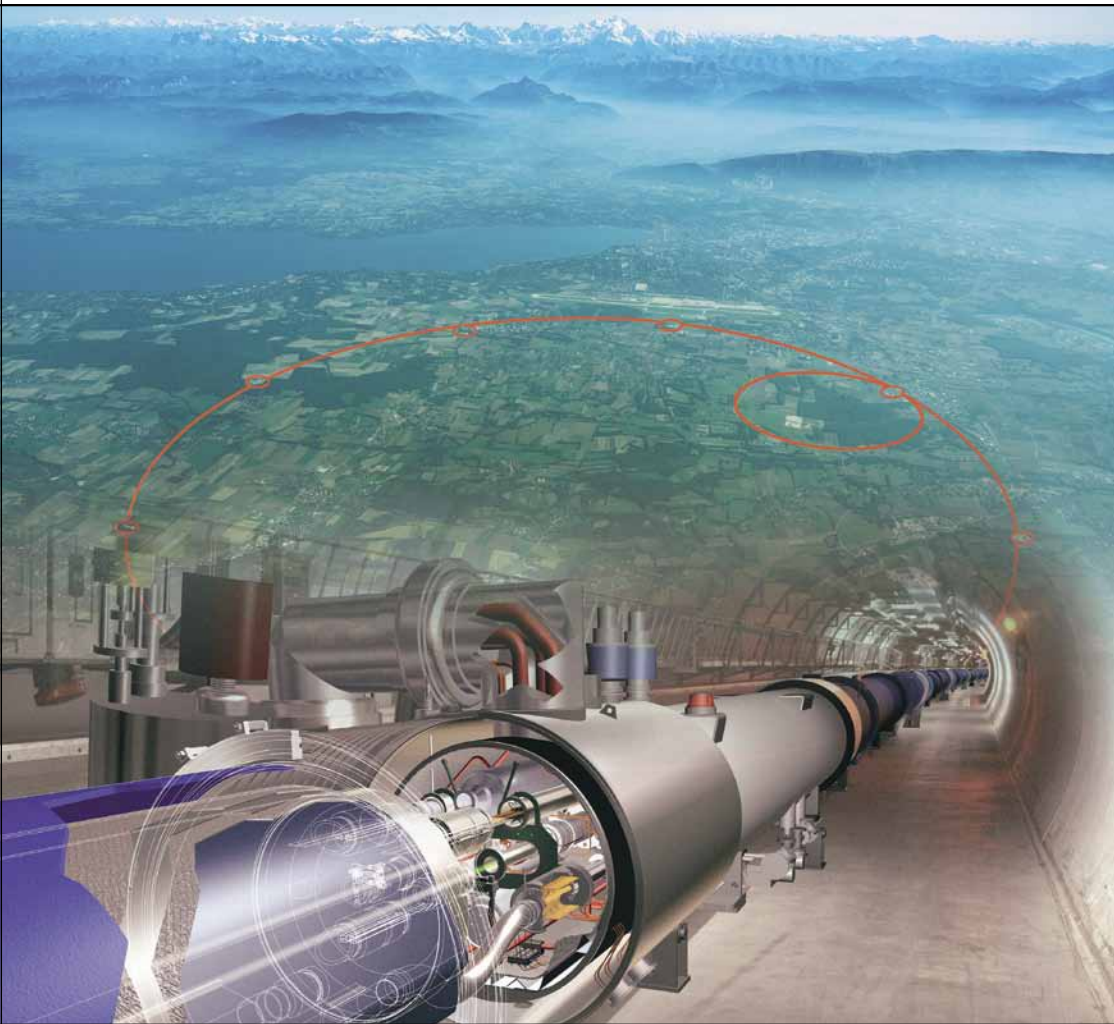
In the earliest particle accelerators — Van de Graaff and Cockcroft-Walton devices — a static electric field accelerated charged particles to higher energies than conventional voltage sources could deliver. In the 1920's the work of Rolf Wideröe, a Norwegian engineer, pointed directly toward the modern 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, technology advances have driven a million-fold increase in accelerator energies, which now exceed 1 trillion volts. The field has progressed from accelerator beams that strike stationary targets and must overcome their inertia. Now counter-rotating beams collide head-on and make full use of both beams' energy. The biggest accelerators stretch for miles.

Today's highest-energy accelerators include one at the national accelerator laboratory at Stanford University (SLAC). There electrons collide head-on with positrons (electrons' anti-particles) to produce copious numbers of B-mesons — fascinating particles with unusual properties.



COPYRIGHT CERN.

The Large Hadron Collider (LHC) — straddling the Swiss-French border near Geneva — has embarked on a new era of discovery. Experiments there will 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.

US scientists and engineers, supported by the US Department of Energy Office of Science and the National Science Foundation, have helped build 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.

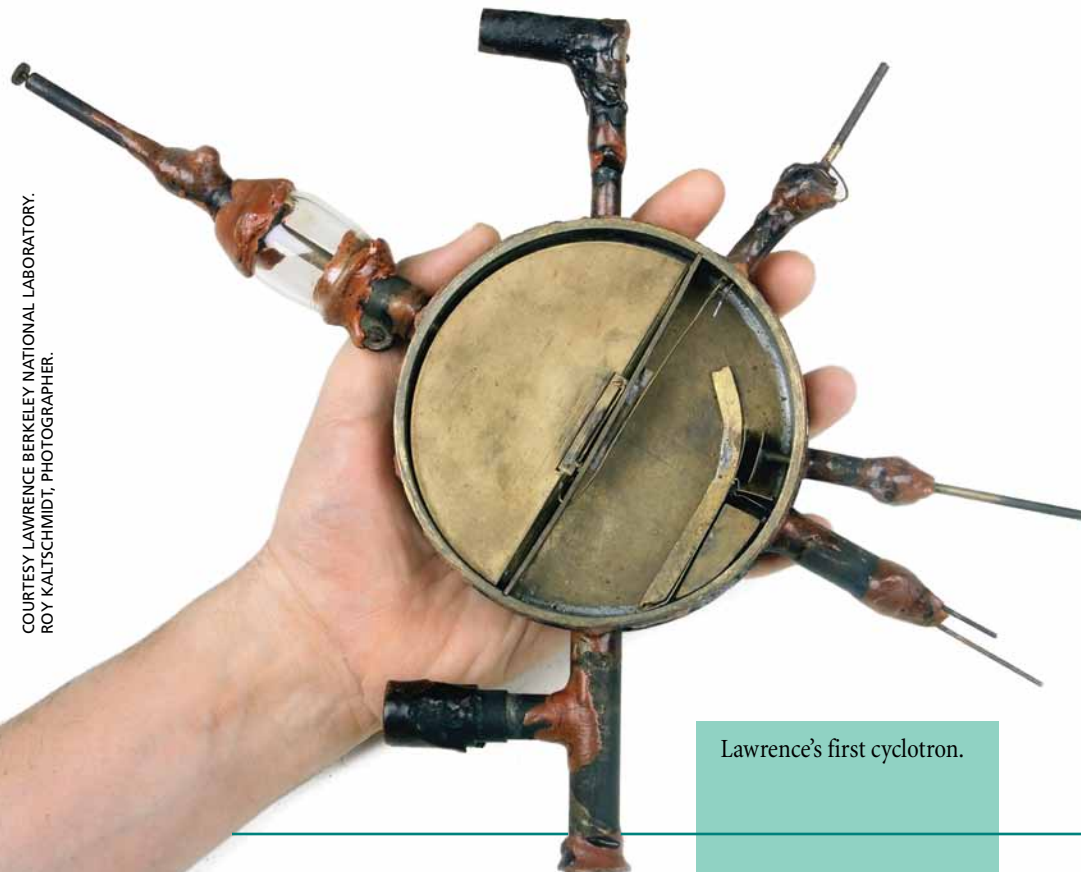
# particle accelerators

The Fermilab Tevatron in Illinois, until recently the world's highest-energy accelerator, collides protons with antiprotons and produces the top quark, the heaviest elementary particle known.

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

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

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 an accelerator, accelerator physicists work with engineers to design, build, install, commission and operate components like those described here and on the facing page.



COURTESY JEFFERSON LABORATORY.

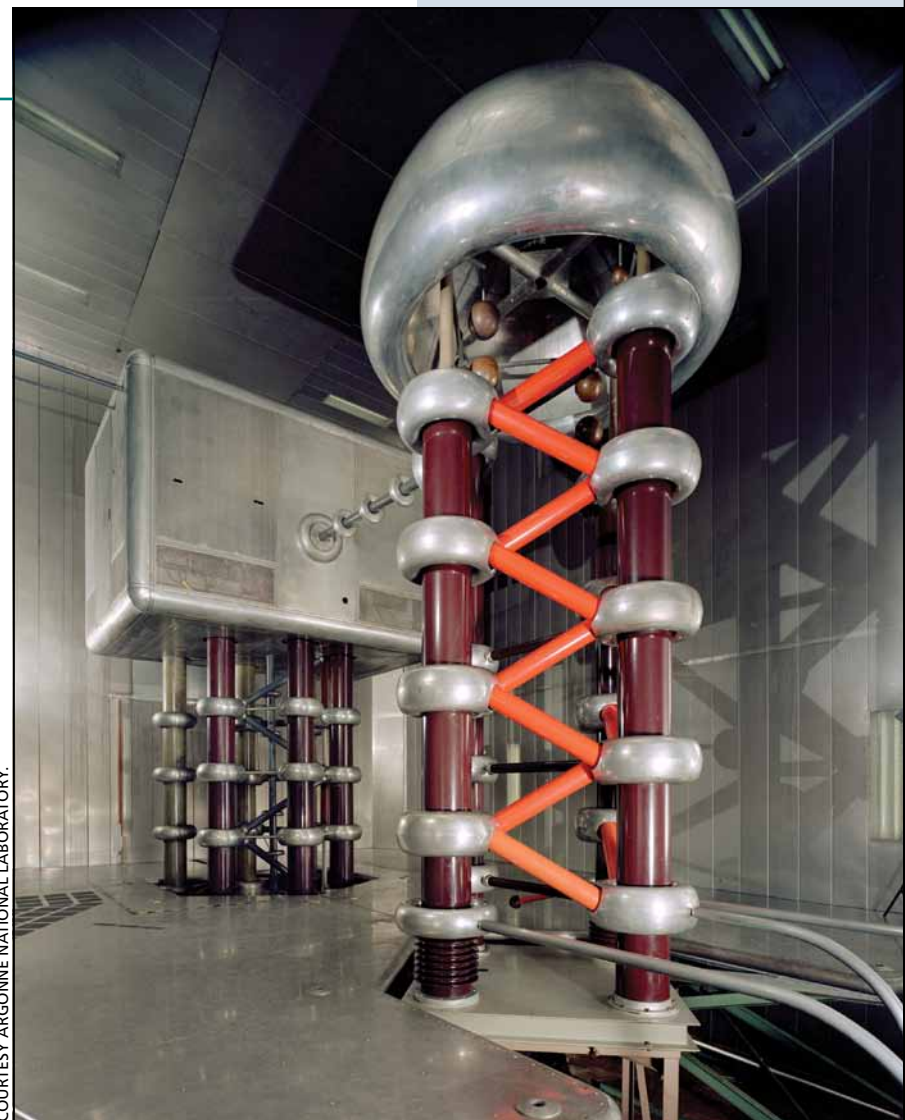
**B, C.** Magnets and vacuum chambers at Jefferson Laboratory. Visible here are a focusing magnet (red), a bending magnet (light blue) and the stainless steel vacuum chamber (beam pipe).



COURTESY CERN.

COURTESY ARGONNE NATIONAL LABORATORY.

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



**A.** The ion source and Cockcroft-Walton preaccelerator in the Intense Pulsed Neutron Source at Argonne National Laboratory.

**A. The ion source** produces the 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 center.

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.



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

COURTESY JEFFERSON LABORATORY.

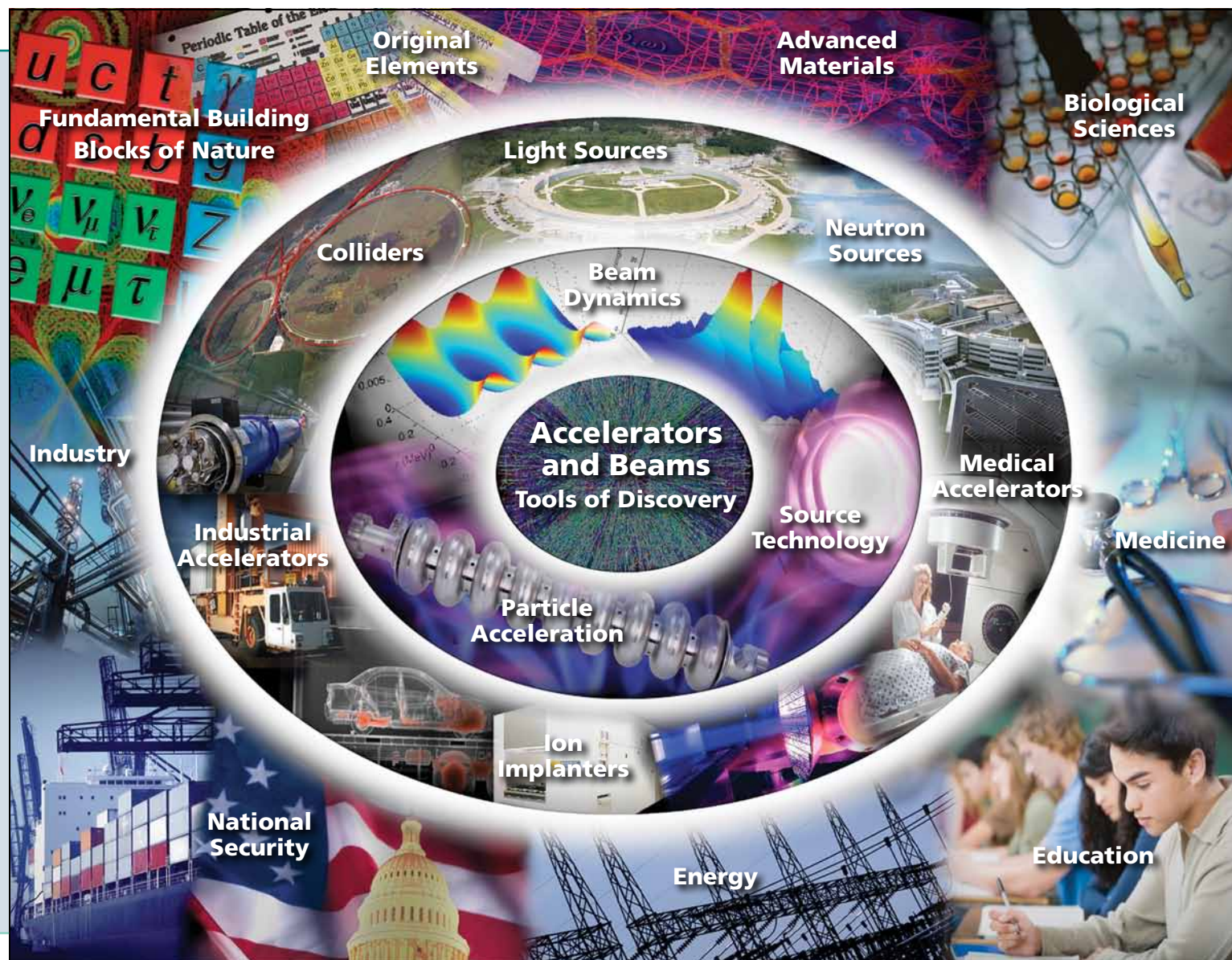


**G. Jefferson Laboratory accelerator control center.**

COURTESY FERMILAB.



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



# Applications of accelerators

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 (or particle physics), common particles are accelerated to energies far higher than usually found on earth. Collisions then produce particles that do not normally exist in nature, yielding data on the properties of these new particles — fundamental information about nature itself.

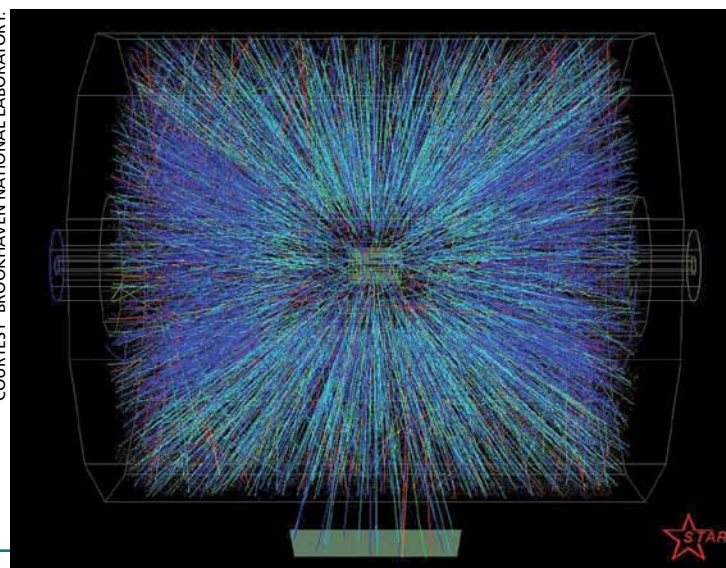
Nuclear physics uses the energy of beams to study the internal dynamics of the atom's nucleus or the dynamics when nuclei interact. Sometimes this results in producing isotopes that do not normally exist in nature.

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

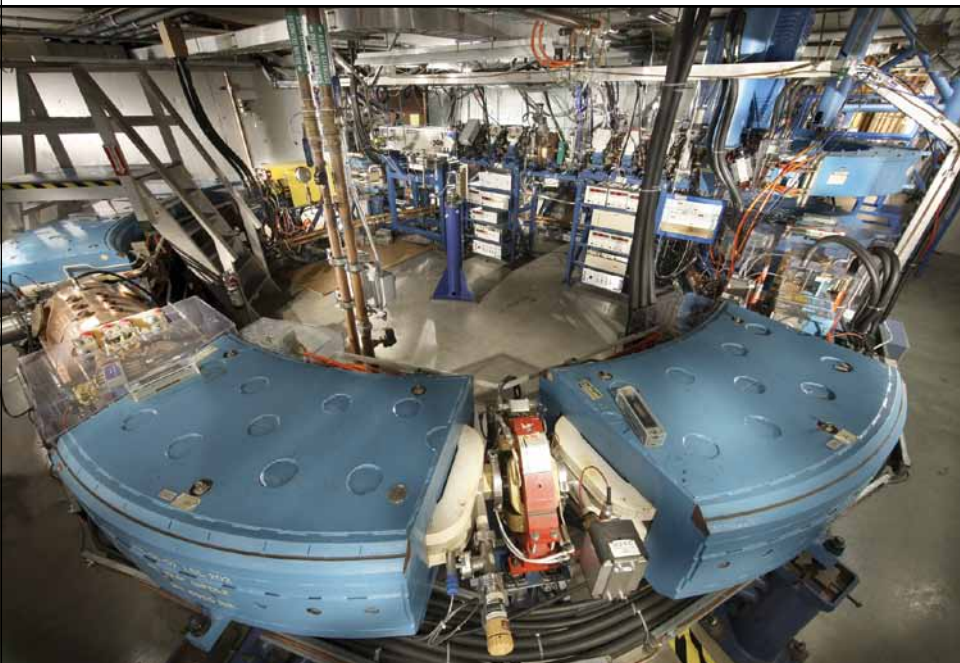
Across the country and around the world, hospitals and doctors use thousands of medical accelerators.

Some accelerators produce radioactive substances for medical imaging, aiding diagnosis of cancer and other conditions via techniques like positron emission tomography (PET). Accelerators also

make radioactive isotopes for diagnostic procedures and therapy.

Many medical accelerators produce radiation for directly attacking cancer. Advances in proton 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 treatment 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 for Loma Linda.



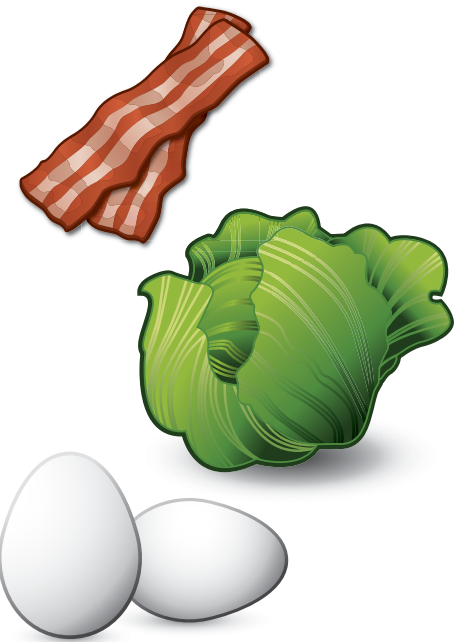
IMAGE COURTESY OF VARIAN MEDICAL SYSTEMS OF PALO ALTO, CALIFORNIA. ©2009 VARIAN MEDICAL SYSTEMS. ALL RIGHTS RESERVED.

# Accelerators to beat food-borne illness

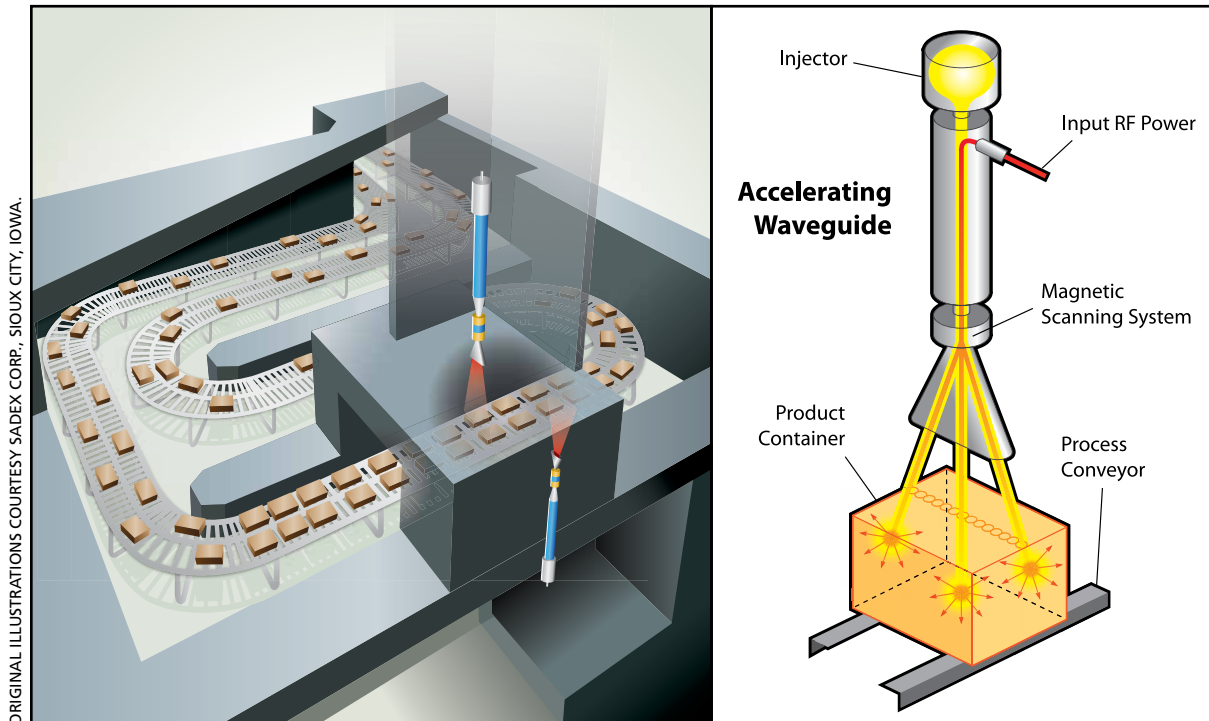
Every week in the United States, about 100 people die from food-borne illness, even though electron accelerators can make food much safer, just as pasteurization makes milk much safer. Electron beams, or X-rays derived from them, can kill dangerous bacteria like *E. coli*, salmonella and listeria.

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.



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.

# Accelerators and national security

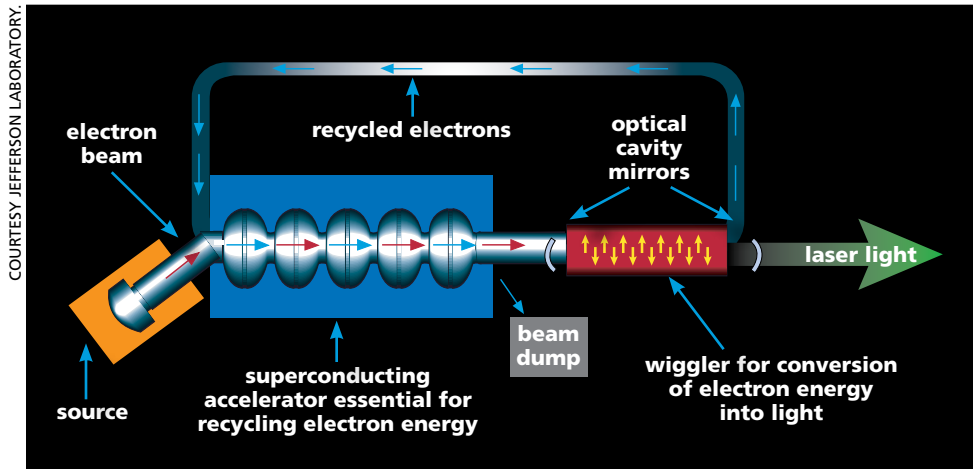


Diagram of the Jefferson Laboratory FEL. Electrons are released from the source at the lower left, and are accelerated in a superconducting linear accelerator. The electrons then pass into a laser cavity. In the cavity center is a wiggler, a series of magnets that deflect the electrons back and forth. This makes the electrons emit light, which is captured in the cavity, and used to induce new electrons to emit even more light. After exiting the optical cavity the electrons travel around the loop at the top and back into the linear accelerator. Here they give up most of their energy to a new batch of electrons, making the process highly efficient.

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.

The US Navy has an intense interest in defending its ships with antimissile directed-energy weapons. One possibility is an onboard free-electron laser (FEL). This kind of laser shares the optical properties of conventional lasers, emitting a beam of coherent light that can reach high power. It is driven by an intense electron beam accelerator. Unlike most conventional lasers, its light's wavelength can be varied. That's a crucial capability for operating in varying atmospheric conditions.



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

COURTESY L-3 COMMUNICATIONS SECURITY & DETECTION SYSTEMS.

# Accelerators validate nuclear weapons performance

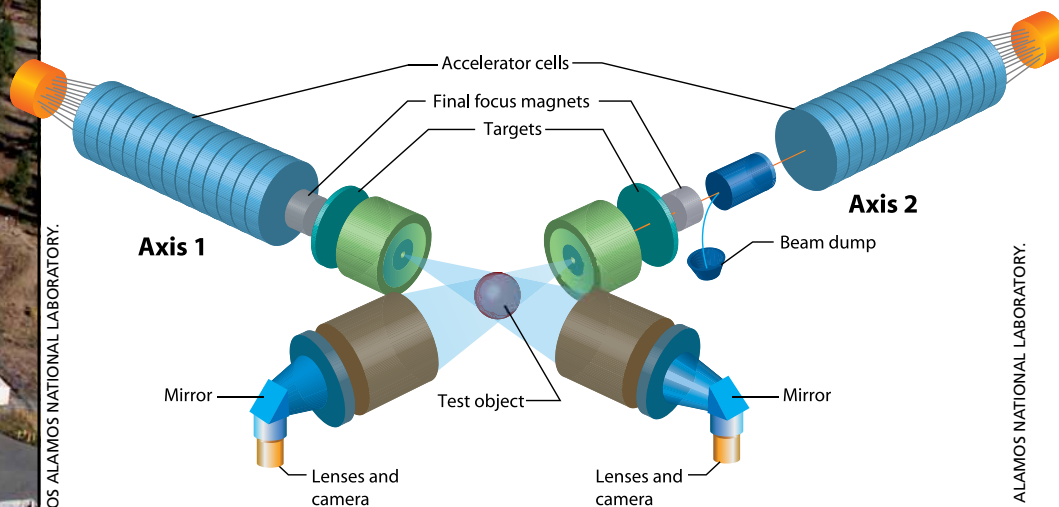


The DARHT Facility at Los Alamos National Laboratory in New Mexico.

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 each weapon's radioactivity gradually degrades its components, and nuclear weapons testing moratoria preclude integrity tests.

In a non-nuclear 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.

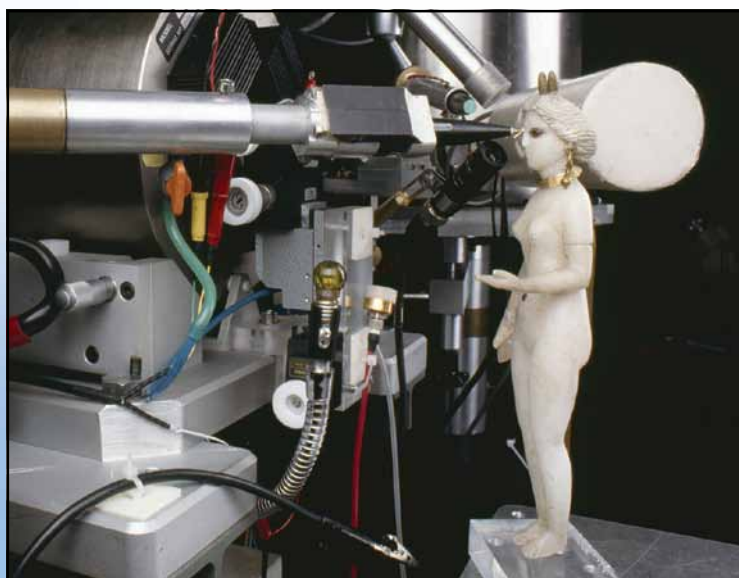
Because the surrogate fuel and the components being tested become hot enough to melt and flow like water, such a test is called hydrodynamic—leading to the name Dual-Axis Radiographic Hydrodynamic Test Facility, or DARHT Facility.



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

# 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 used, 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.

# 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 infrared, visible, ultraviolet, X-ray and gamma-ray light. An equivalent statement is that light sources generate beams of 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 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 beam lines to scientific experiments or technological uses.

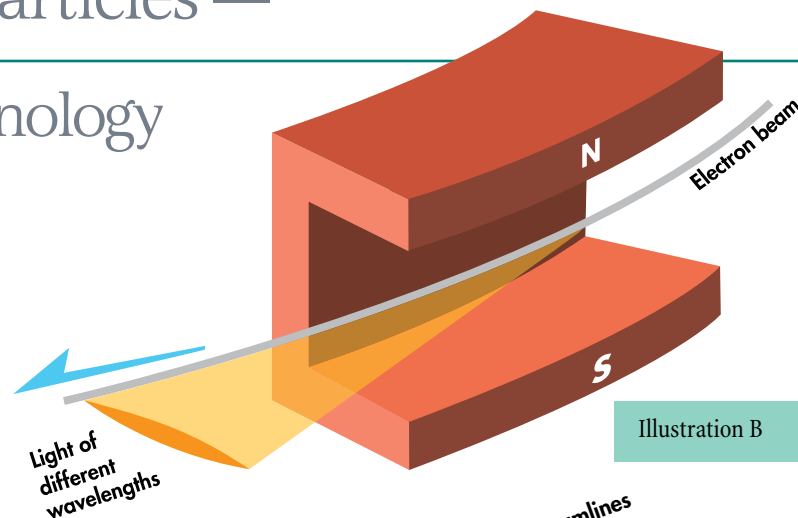


Illustration B

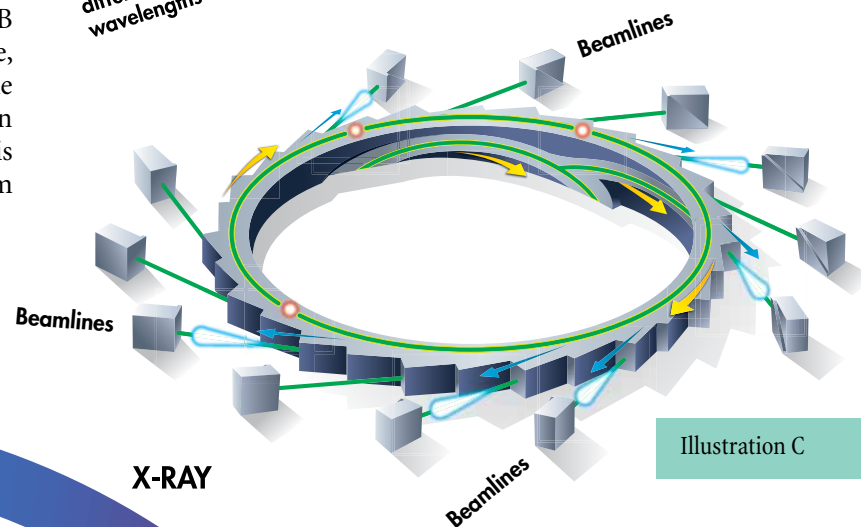


Illustration C

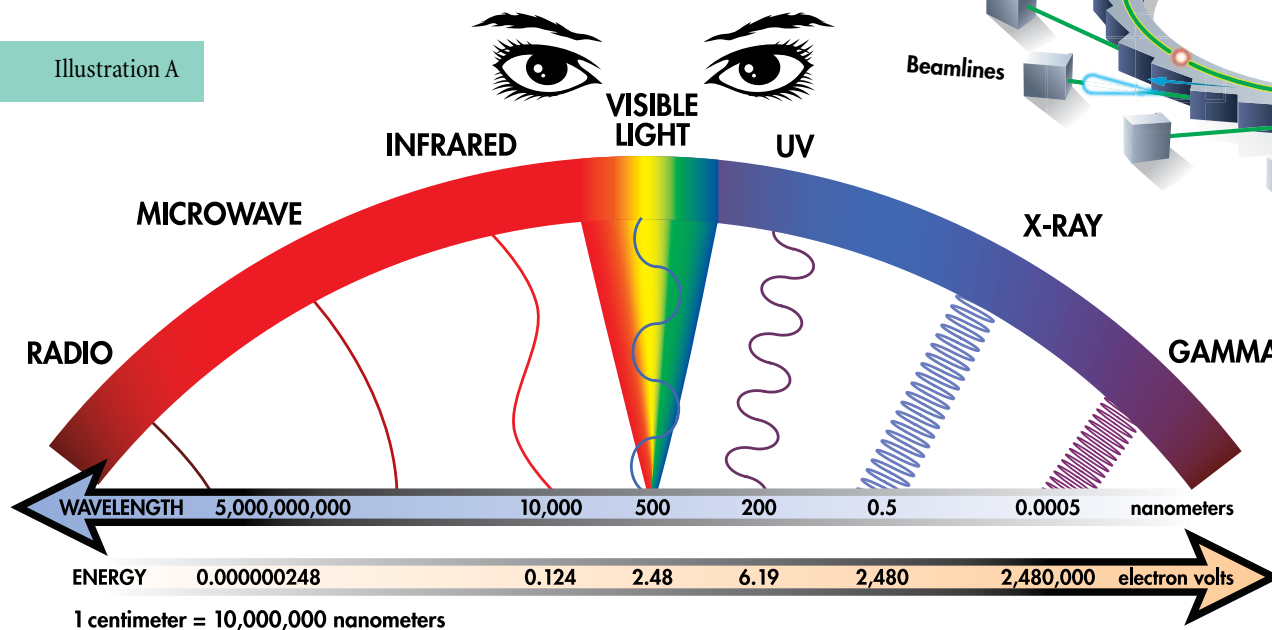
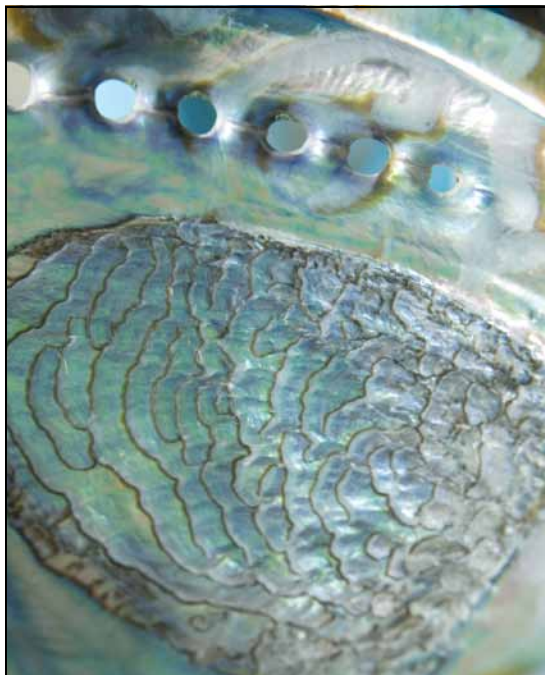


Illustration A

# 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? At the University of Wisconsin, researchers using a light source called Aladdin investigate questions like these.

Aladdin attracts scientists from around the world. They tackle fundamental and applied problems, including experiments involving superconductors, geology, and environmental science. They also conduct microanalysis of cells, tissues, and minerals and cutting-edge explorations of nanotechnology and nanocircuit fabrication.

COURTESY LAWRENCE BERKELEY NATIONAL LABORATORY. ROY KALTSCHMIDT, PHOTOGRAPHER.

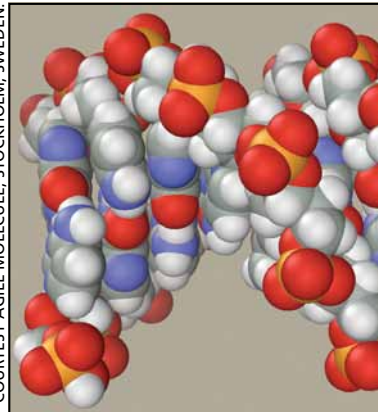


At the Advanced Light Source (ALS) at Lawrence Berkeley National Laboratory, the light is so bright, and can be so finely tuned to specific wavelengths, that it reveals precise details about the arrangement and behavior of atoms and electrons in complex materials.

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 more than 2000 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.

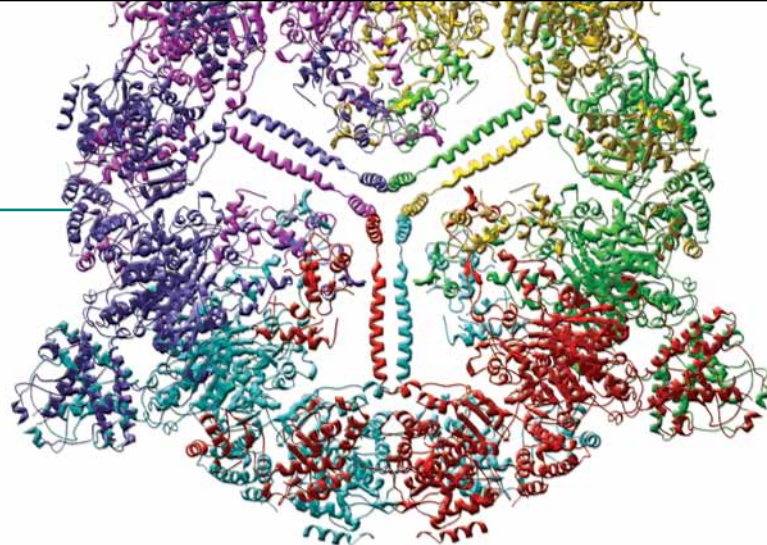
COURTESY AGILE MOLECULE, STOCKHOLM, SWEDEN.



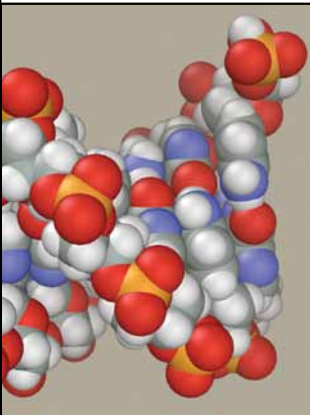
COURTESY NATIONAL SYNCHROTRON LIGHT SOURCE,  
BROOKHAVEN NATIONAL LABORATORY.



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.



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

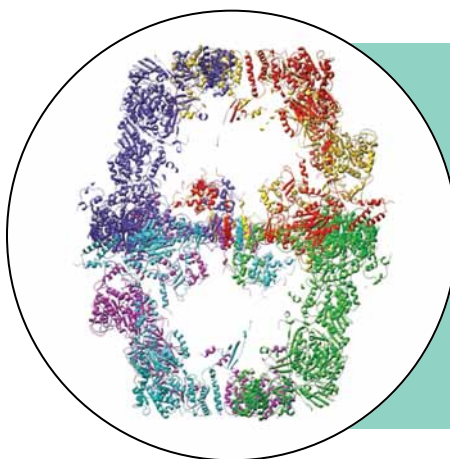


THE SCALE FOR  
THESE SCIENTIFIC  
REPRODUCTIONS  
IS THE ORDER  
OF A FEW  
NANOMETERS  
(1 BILLIONTH  
OF A METER).

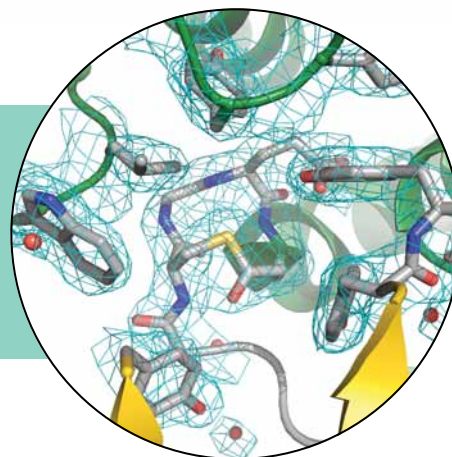
At Argonne National Laboratory scientists use the brilliant beam from the Advanced Photon Source to reveal how proteins function. The Human Genome project identified 20,000 to 25,000 genes in human DNA that regulate everything from breathing to digestion and sweating. Understanding how DNA generates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

# Accelerators for improving materials' surfaces

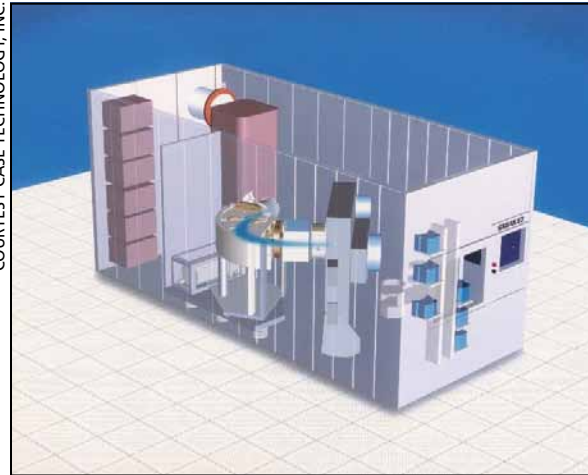
An accelerator-based manufacturing technique called ion implantation modifies semiconductors' electrical properties precisely and cost-effectively, leading to better, cheaper electronics.

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.

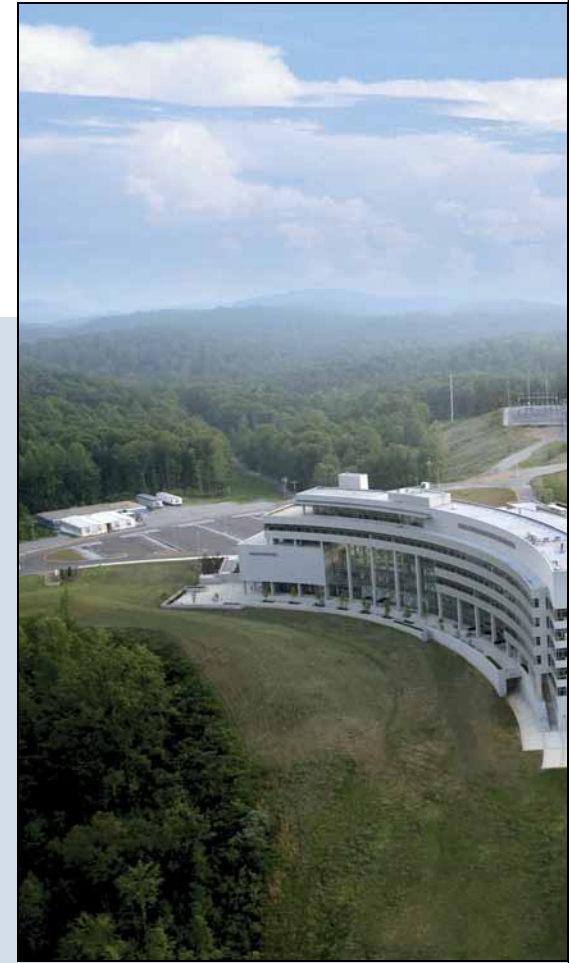


A typical ion implanter.

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 one-of-a-kind, 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.

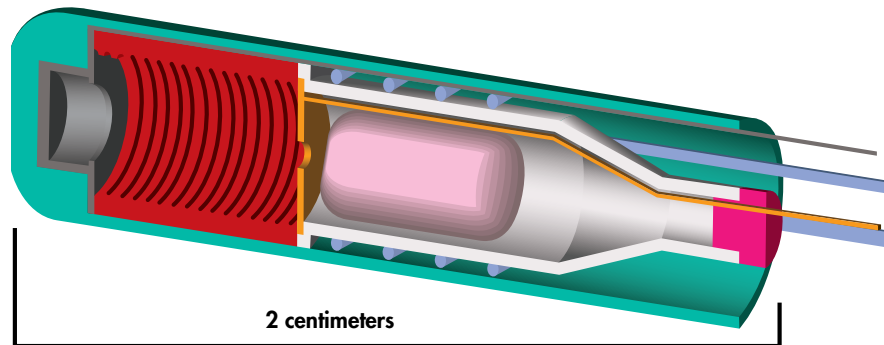
PHOTO ALEX NEEDHAM (WIKIPEDIA).

# 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 find oil.

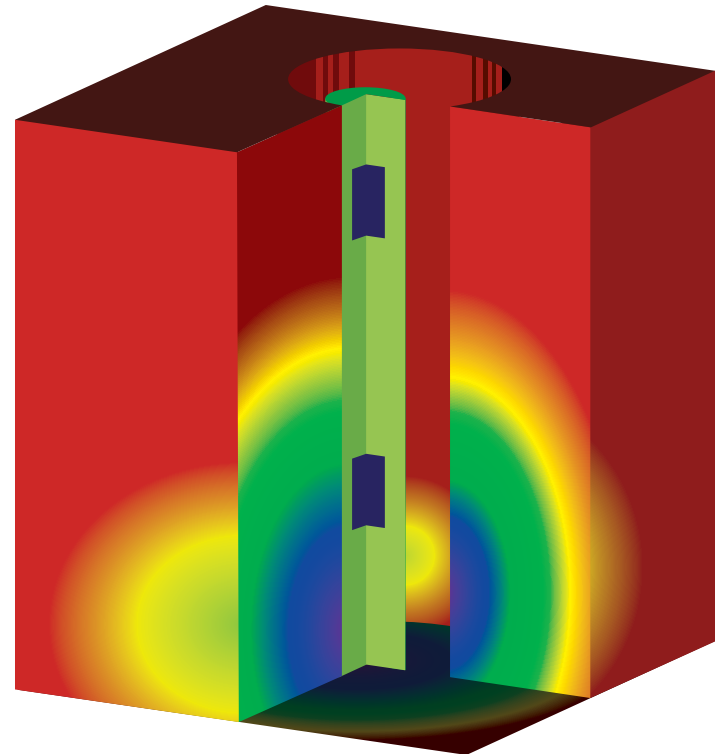
The accelerator generates the neutrons by manipulating isotopes of hydrogen. It can discover oil deposits by detecting porosity, which shows the presence of liquid or gas. Electrical characteristics tell whether a liquid is water or oil.

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.



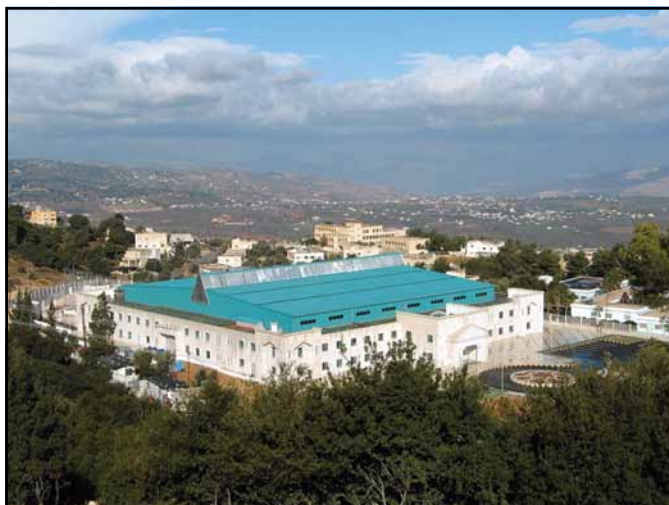
FROM AN IMAGE BY  
LAWRENCE LIVERMORE NATIONAL LABORATORY.

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 under UNESCO auspices, 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 sciences.



The SESAME site and building.



The microtron, first link in the accelerator chain, now installed and operating at SESAME, is part of a decommissioned facility donated by Germany. Next will be assembly of the booster ring, which will inject electrons into a much larger, new main ring.

PHOTO COURTESY RAFFIK SARRAF (SESAME).

PHOTO COURTESY MACIEJ NALECZ (UNESCO).

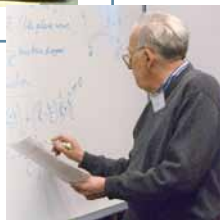
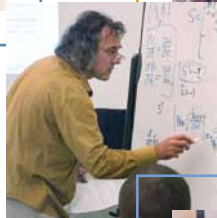
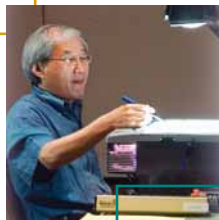
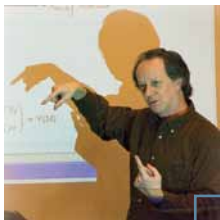
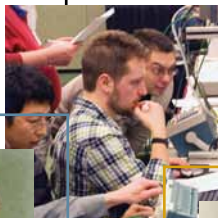
# Education and

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 design and 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.



# 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 immersive 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  
(MIDDLE RIGHT) COPYRIGHT CEA, L. GODARD, AND  
(BOTTOM LEFT) JEFFERSON LABORATORY.

# 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 plan and use high-intensity, low-energy beams to explore reactions at stellar energies.

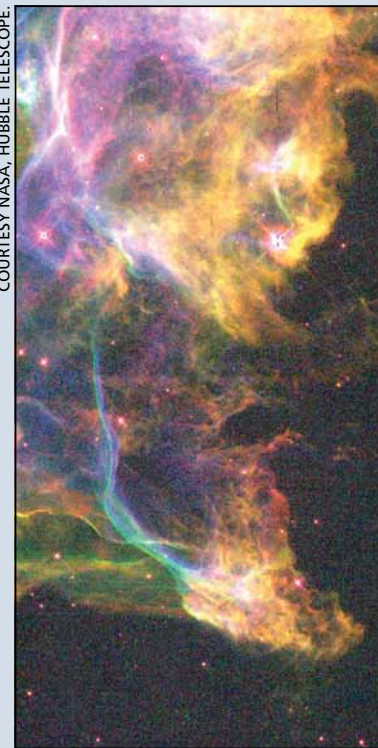
The newly approved Facility for Rare Isotope Beams, to be constructed at Michigan State University, will provide intense beams of rare isotopes, short-lived atomic nuclei not normally found on Earth. This facility will enable researchers to address questions such as: What is the origin of the elements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



COURTESY NASA, HUBBLE TELESCOPE.

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

COURTESY NASA, HUBBLE TELESCOPE.



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

# Looking to the future

At the highest-energy frontier of physics, Europe's Large Hadron Collider (LHC) is delivering exciting new findings. For over three decades, such facilities have yielded 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, or Fermilab's proposed Project X.

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 comparatively modest studies of possibilities for future generations of colliders should be sustained, extending work carried out at Fermilab and the LHC.

“The remarkable discoveries” over more than 75 years of particle physics “were made possible because of progress and innovation in accelerator science and technology. Accelerators significantly impact the economy, health, and security. The future of accelerator-based science and applications will be limited unless new ideas and new accelerator directions are developed. A major challenge for the accelerator science community is to identify and develop new concepts for future energy frontier accelerators that will be able to provide the exploration tools needed for high-energy physics (HEP) within a feasible cost to society.”

— From the US Dept. of Energy High Energy Physics Advisory Panel (HEPAP) Subpanel Report on the Assessment of Advanced Accelerator Research and Development.

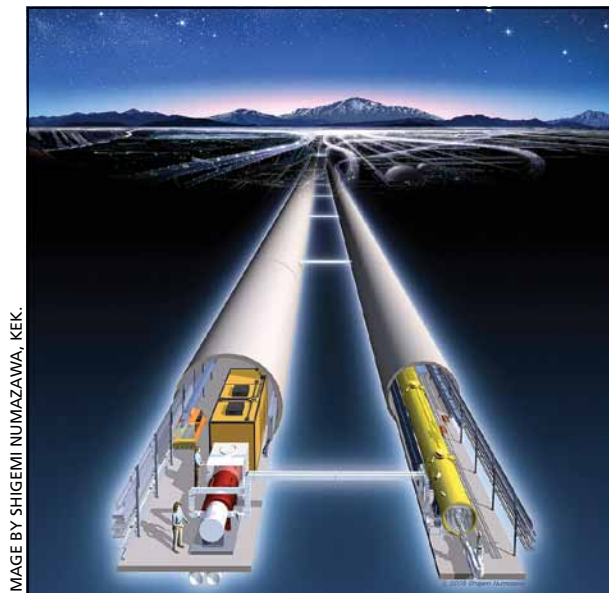
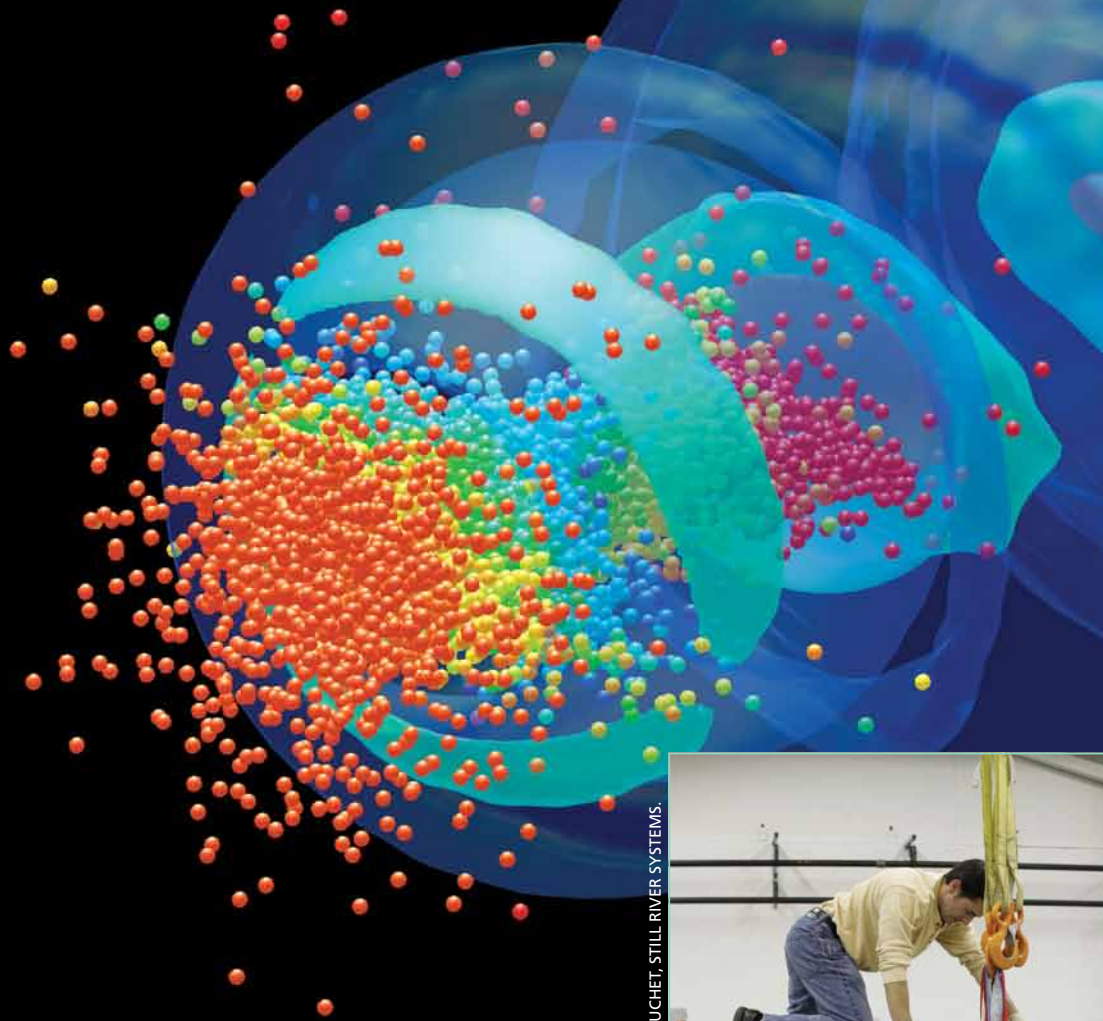


IMAGE BY SHIGEMI NUMAZAWA, KEK.

Consisting of two linear accelerators that face each other, the International Linear Collider will hurl electrons and their anti-particles, 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 of the machine. The machine will stretch approximately 31 kilometers. The beams will collide 14,000 times every second at extremely high energies — 500 billion electron volts (GeV).

# Fundamental R&D



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.

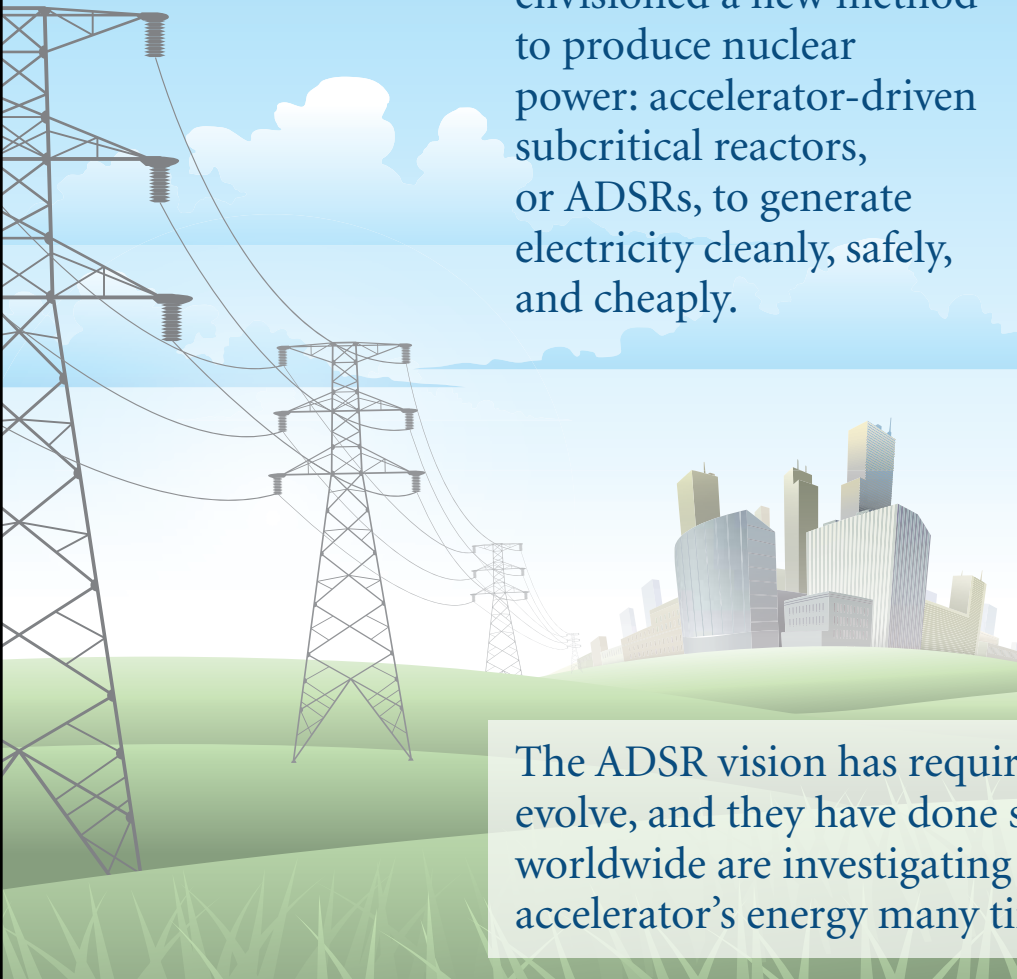


Full-scale model of the radio-frequency cavity of a superconducting cyclotron design of the AIMA Company for high-energy proton therapy.

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 ADSRs, to generate electricity cleanly, safely, and cheaply.

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

An ADSR 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 ADSR 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 ADSR, proton beams from an accelerator would produce them.

The abundant element thorium would likely serve as fuel for an ADSR, also called an “energy amplifier.”

The ADSR 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

Accelerator science has a profound impact on society as a whole. There are well-established applications of accelerator science and technology in diagnostic and therapeutic medicine for research and for routine clinical treatments. A significant fraction of the radioisotopes used in treatment, diagnostics, and research are produced using accelerators. Beams of X-rays, neutrons, protons, and ions that are derived from particle accelerators are currently used in the treatment of cancer and other diseases. Accelerators are also used in many biomedical research programs both to explore beam-related treatments and to develop other approaches to therapy. Each year numerous lives are saved due to the applications of accelerator science to health care. The development and improvement of superconductors for high-field accelerator magnets has had a direct application in the large and competitive MRI medical diagnostic industry. Recently, electron beam-based sterilization of vulnerable components of the national food supply has added to the health benefits attributable to accelerator technology.

Accelerators and associated technologies have various important uses in industry for R&D, manufacturing, testing, and process control. Industrial researchers, in common with materials scientists in universities and national laboratories, use synchrotron radiation, neutron scattering, and other

accelerator-based techniques as important tools in their R&D activities. In industry, the R&D is often undertaken to develop new products – for example, high-density magnetic storage media. In manufacturing, beams from accelerators are used to alter material composition (e.g., ion implantation); to improve important characteristics of a product (e.g., sterilization of medical equipment and the hardening of surfaces for greater wear resistance); as a basic part of the production process (e.g., ion implantation and X-ray lithography in silicon wafer production, or X-ray micromachining); to improve industrial processes (e.g., curing epoxies and plastics); and to provide information about manufacturing processes (e.g., wear studies of materials or characterization of impurities in semiconductors).

National security is also enhanced by the development of particle accelerators. Accelerator techniques, including X-ray and proton radiography hydrodynamic test facilities, can be used to test the reliability and aging of nuclear weapons without detonation. Accelerator-based systems have been developed to allow rapid screening of cargo containers to discover contraband nuclear materials.

*– From the HEPAP Subpanel Report on the Assessment of Advanced Accelerator Research and Development.*

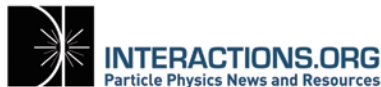
# To learn more



Dimensions of Particle Physics, a joint Fermilab/SLAC publication  
<http://www.symmetrymagazine.org>



News, information, and educational materials about the world's synchrotron and free-electron laser light source facilities. <http://lightsources.org>



Particle Physics News and Resources, a communications resource from the world's particle physics laboratories. <http://www.interactions.org>



International Journal of High-Energy Physics. <http://cerncourier.com/cws/latest/cern>  
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An award-winning interactive tour of quarks, neutrinos, antimatter, extra dimensions, dark matter, accelerators and particle detectors from the Particle Data Group of Lawrence Berkeley National laboratory.  
<http://particleadventure.org/accel.html>



*Physical Review Special Topics - Accelerators and Beams* is an online-only journal where basic research papers communicating new results in accelerator science are published for specialists. The journal is freely available on the Internet and is supported by a world-wide consortium of accelerator laboratories.  
<http://prst-ab.aps.org>

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.

# Accelerators AND Beams

TOOLS OF DISCOVERY AND INNOVATION

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