Accelerators for America's Future

U.S. DEPARTMENT OF ENERGY

ACCELERATORS FOR AMERICA'S FUTURE

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Prosperity, security, health, energy, environment. Meeting these 21st-century challenges—and seizing the opportunities they bring—will determine the shape of America's future. The science and technology of particle accelerators can contribute to our success. Today, besides their role in scientific discovery, particle beams from some 30,000 accelerators are at work worldwide in areas ranging from diagnosing and treating disease to powering industrial processes.

The accelerators of tomorrow promise still greater opportunities. Next-generation particle beams represent cheaper, greener alternatives to traditional industrial processes. They can give us clean energy through safer nuclear power, with far less waste. They can clean up polluted air and water; deliver targeted cancer treatment with minimal side effects; and contribute to the development of new materials. As tools for inspecting cargo and improving the monitoring of test ban compliance, accelerators can strengthen the nation's security.

Other nations are already applying next-generation accelerator technologies to current-generation issues—and challenging United States leadership in accelerator innovation. To remain competitive will require a sustained and focused national effort, along with changes in policy.

Advances in accelerator technology most often come from basic science. The Department of Energy's Office of Science has launched an initiative to encourage breakthroughs in accelerator science and their translation into applications for the nation's health, wealth and security. At an inaugural workshop, experts from across the spectrum of accelerator applications identified opportunities and challenges for particle beams in energy and environment, medicine, industry, national security and discovery science. "Accelerators for America's Future" captures their perspectives, insights and conclusions, informing a national program to put accelerators to work on the challenges of our time.

A MESSAGE FROM THE CHAIRS

In October 2009, the Department of Energy's Office of High Energy Physics sponsored a symposium and workshop, "Accelerators for America's Future." Its purpose was to elicit the views and opinions of a wide range of accelerator users on the challenges and opportunities for developing and deploying accelerators to meet national needs. Some 300 of them attended the one-day symposium and poster session. In the two-day workshop that followed, 120 users of accelerator technology, from small business owners to well-known researchers, formed five working groups in Energy and Environment, Industry, Medicine, National Security and Discovery Science. Their charge was to give us their perspective on needs, challenges and areas of greatest promise; and to provide guidance on bridging the gap between accelerator research and technology deployment. For two days, they discussed, disagreed, concurred, consulted, reconsidered—and eventually converged on results. The groups' reports varied in scope, approach and level of technical detail. Sometimes their findings conflicted. The workshop was designed as an inclusive, broad-spectrum effort to learn from stakeholders with boots on the ground in fields that depend on accelerator science and technology. This report captures what they told us. We present it as a resource for agencies as they develop their agendas and programs.

Walter Henning **Charles Shank**

"Accelerators for America" Symposium and Workshop Chairs

June 2010

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Accelerators for America's Future

A beam of particles is a very useful tool.

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.

PARTICLE BEAMS TO MEET NATIONAL CHALLENGES

The beams produced by today's particle accelerators address many of the challenges confronting our nation in the 21st century: energy, the environment, good jobs and economic security, health care, national defense and the war on terror. The next-generation accelerators of tomorrow have the potential to make still greater contributions to the nation's health, wealth and national security.

Incorporating innovative accelerator technologies into tomorrow's nuclear energy supply, for example, has the potential to make nuclear power safer and cleaner with far less nuclear waste. Electron beams could treat flue gases to make coal-fired plants cleaner and more environmentally friendly. They could detoxify waste water and make municipal water safe to drink. Advances in beam therapy offer the promise of improving cancer treatment by maximizing the beam energy delivered to a tumor while minimizing the damage to normal tissue. Accelerators could serve as reliable alternative sources of critically needed medical isotopes currently made in nuclear reactors—some no longer produced at all in the United States. In industry, accelerators represent cheaper, greener alternatives to hundreds of traditional manufacturing processes. For security and defense, compact, rugged, "fieldable" accelerators would have innovative applications from safe and reliable cargo inspection to monitoring international test ban compliance. The continuing development of accelerator technology will give scientists the tools for discovery across a spectrum of science from particle physics to human biology.

For the United States to remain competitive in accelerator science and technology, however, will require a sustained and focused program and changes in national policy.

Photo: Sandbox Studio

Tens of thousands of accelerators are at work every day producing particle beams in hospitals and clinics, in manufacturing plants and industrial laboratories, in ports and printing plants and, literally, on the ships at sea.

PRACTICAL PARTICLES

The marquee superstars of the particle accelerator world are the giant research accelerators like Fermilab's Tevatron, Brookhaven's Relativistic Heavy Ion Collider, and most recently CERN's Large Hadron Collider in Geneva, Switzerland. Behind the headlines, though, are the tens of thousands of accelerators that are at work every day producing particle beams in hospitals and clinics, in manufacturing plants and industrial laboratories, in ports and printing plants and, literally, on the ships at sea. Adding them all up, some 30,000 particle accelerators operate in the world today in medicine, industry, security and defense and basic science. The market for medical and industrial accelerators currently exceeds $3.5 billion dollars a year, and it is growing at more than ten percent annually. All digital electronics now depend on particle beams for ion implantation, creating a $1.5 billion annual market for ion-beam accelerators. All the products that are processed, treated or inspected by particle beams have a collective annual value of more than $500 billion.

Other nations have not been slow to recognize the potential for future applications of accelerators. European and Asian nations are already applying next-generation accelerator technology to current-generation challenges. In March 2010, the Belgian government approved $1.3 billion for the MYRRHA project. It will demonstrate an accelerator-driven system for producing nuclear power and transmuting nuclear waste to a form that decays much faster to a stable non-radioactive form. The Belgian government estimates that the project will create 2000 long-term jobs. In China and Poland, accelerators are turning flue gases into fertilizer; and Korea operates an industrial-scale water-treatment plant using electron beams. Cancer patients in Japan and Germany can now receive treatment with light-ion beams, and clinical centers with multiple ion beams are coming on line across Europe. U.S. patients don't have these options.

The United States, which has traditionally led the world in the development and application of accelerator technology, now lags behind other nations in many cases, and the gap is growing. To achieve the potential of particle accelerators to address national challenges will require a sustained focus on developing transformative technological opportunities, accompanied by changes in national programs and policy.

FROM SCIENCE TO SOCIETY

Historically, breakthroughs in accelerator technology have most often come from the realm of basic science research. The human imperative to discover the laws of nature, from the most fundamental interactions of matter to the behavior of the most complex biological systems, drives the search for ever more powerful investigative tools. Writing in 1916, J.J. Thomson, discoverer of the electron, described a famous example of the application of basic science research to immediate practical needs.

"By research in pure science," Thomson wrote, "I mean research made without any idea of application to industrial matters but solely with the view of extending our knowledge of the Laws of Nature. I will give just one example of the 'utility' of this kind of research, one that has been brought into great prominence by the War—I mean the use of X-rays in surgery…

"Now how was this method discovered? It was not the result of a research in applied science to find an improved method of locating bullet wounds. This might have led to improved probes, but we cannot imagine it leading to the discovery of the X-rays. No, this method is due to an investigation in pure science, made with the object of discovering what is the nature of Electricity."

Since the days of cathode ray tubes in the 1890s, particle accelerators have made an extraordinary evolution as tools of basic science. Between Ernest Lawrence's first four-inch-diameter cyclotron, built at Berkeley in the 1930s, and today's most powerful particle accelerator, the 16-mile-circumference Large Hadron Collider, have come dozens of progressively more powerful and precise machines, each incorporating innovations and breakthroughs to advance scientific progress. Each generation of particle accelerators builds on the accomplishments of the previous ones, raising the level of technology ever higher, a thrust that continues today. The National Academy of Engineering lists "to engineer the tools for scientific discovery" among its "Grand Challenges for the 21st Century."

Continued U.S. innovation in accelerator technology rests on the next generation of accelerator scientists and engineers.

BRIDGING THE VALLEY OF DEATH

Just as the investigation of electricity led to the discovery of x-rays, which found immediate use, the future of particle accelerators belongs not just to scientists. The powerful new accelerator technologies created for basic science and developed by industry will produce particle accelerators with the potential to address key economic and societal issues confronting our nation.

A critical challenge is the translation of breakthroughs in accelerator science and technology into applications that benefit the nation's health, wealth and security. Experts from every field of accelerator science and technology, in the research community and industry alike, agree that making that happen will require bridging the divide often described as the "valley of death" that exists in the United States today between the research laboratory and the marketplace.

On one side of the valley are the innovative accelerator concepts and technologies that emerge, often in government-funded laboratories and universities, for basic research. On the other are industries that could put these new technologies to work to meet national needs—and compete in the global marketplace. Keeping them apart are a dearth of funding mechanisms for research and development; a lack of national facilities, demonstration projects and pilot programs to assist with the translation; an aversion to risk; and policies that inhibit coordination and partnership among government entities and between government and industry.

A Fermilab exhibit illustrates the contributions of particle accelerators to society.
Photo: Reidar Hahn, Fermilab

For optimizing knowledge-based resources in science and technology, and for sustaining an environment for new and revitalized industries and the well-paying jobs they bring, a beam of particles is a very useful tool.

A PATH FORWARD

To address the challenge of innovation for national competitiveness in the domain of particle accelerators, the Department of Energy's Office of Science, the nation's major steward of accelerator technology, has inaugurated a program to coordinate basic and applied accelerator R&D. To better understand the direct connection between fundamental accelerator technology and applications, the Office of High Energy Physics sponsored an October 2009 workshop on behalf of the Office of Science to identify the R&D needs of the various users of accelerators who would benefit from future technology R&D initiatives. Accelerator users and experts at the workshop focused on the potential role of accelerators in five key areas: energy and the environment, medicine, industry, national security and defense, and discovery science. They identified the opportunities and research challenges for next-generation accelerators; the most promising avenues for new or enhanced R&D efforts; and a path forward to stronger coordination between basic and applied research.

The accelerator stakeholders articulated the technical challenges and risks involved in achieving their vision for future accelerators and focused on changes in policy that would help to make the vision a reality. Across the board, all groups strongly advocated the creation of large-scale demonstration and development facilities to help bridge the gap between development and deployment of accelerator technologies. They called for greatly improved inter-agency, interprogram, and industry-agency coordination. Because continued innovation in accelerator technology depends on the next generation of accelerator scientists, they emphasized the need to strengthen the training and education of U.S. accelerator scientists and engineers, and to recognize accelerator science as a scientific discipline. The Office of Science will use the workshop's results, presented in this report, to develop a strategic plan for accelerator technology R&D that recognizes its broad national impacts.

The 2005 National Academies report, *Rising Above the Gathering Storm*, issued a national call to action to address the eroding technological building blocks of future prosperity in the United States.

"This nation must prepare with great urgency to preserve its strategic and economic security," said the report's major finding. "Because other nations have, and probably will continue to have, the competitive advantage of low-wage structure, *the United States must compete by optimizing its knowledge-based resources, particularly in science and technology, and by sustaining the most fertile environment for new and revitalized industries and the well-paying jobs they bring*. (Italics added.) We have already seen that capital, factories, and laboratories readily move wherever they are thought to have the greatest promise of return."

For optimizing knowledge-based resources in science and technology, and for sustaining an environment for new and revitalized industries and the well-paying jobs they bring, a beam of particles is a very useful tool.

"Accelerators for America's Future," an October 2009 symposium and workshop, brought together stakeholders from across the spectrum of accelerator science and technology.
Photo: Reidar Hahn, Fermilab

Accelerators for Energy and the Environment

According to the Energy Information Administration of the United States Department of Energy, from 2006 to 2030:

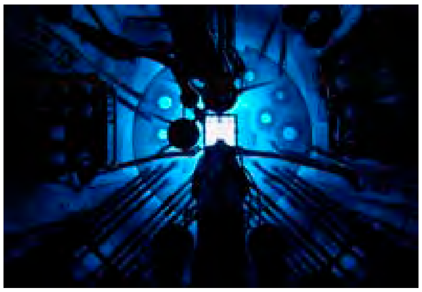
- World marketed energy consumption is projected to increase by 44 percent.
- World net electricity consumption is projected to increase by 77 percent.
- World coal consumption is projected to increase by 50 percent.
- World nuclear power generation is projected to increase by 40 percent but drop from 15 percent to 12 percent of total power generation.
- World CO_2 emissions are projected to increase by 40 percent.

Further, United Nations Environment Program studies estimate that two-thirds of the human population will live under water-stress conditions.

Accelerators have extraordinary potential to address these energy and environmental challenges. They are already at work in the area of energy and the environment. Scientists use neutron and x-ray beams from the nation's neutron and photon sources to develop advanced materials, explore hydrogen storage, exploit bio-energy, revolutionize power transmission on the electrical grid, explore carbon sequestration, and improve solar technology.

To meet rapidly growing demand for energy and preserve the environment for coming generations, future energy sources must be abundant, safe, clean and economical. Nuclear energy is a reliable and abundant source of electricity that does not emit greenhouse gases and reduces dependence on foreign oil. Nuclear energy could also generate electricity for electric vehicles and for hydrogen and synthetic fuel production. Tremendous opportunities, largely untapped, exist for deploying accelerator technology to achieve sustainable and safe nuclear energy sources with manageable waste, proliferation control and a greatly reduced carbon footprint.

According to the Energy Information Administration of the U.S. Department of Energy, from 2006 to 2030, world net energy consumption is projected to increase by 44 percent. *Photo: Reidar Hahn*



The high-energy beta particles from spent nuclear fuel give rise to a blue glow known as Cerenkov radiation. ***Photo courtesy of Australian Nuclear Science and Technology Organisation***

Accelerator-driven systems could provide a long-term strategy for the growth of nuclear power in the United States.

A key challenge facing the nuclear fuel cycle is reducing the radiotoxicity and lifetime of spent nuclear fuel. Partitioning or sorting of nuclear waste isotopes and accelerator-based transmutation combined with geological disposal can lead to an acceptable societal solution to the problem of managing spent nuclear fuel. Accelerators can also drive next-generation reactors that burn non-fissile fuel, such as thorium, that can be burned with the use of particle beams. Both or either of these approaches could lead to an increase in power generation through greenhouse gas emission-free nuclear energy and could provide a long-term strategy for the growth of nuclear power in the U.S.

Accelerators also have a potential role in the development of fusion energy. For magnetically confined nuclear fusion reactors such as the International Thermonuclear Experimental Reactor, or ITER, under development in France by an international consortium, and for subsequent demonstration and commercial power plants, fusion scientists expect ion beams to be part of the mix of plasma heating techniques. More important, they will be part of the plasma current drive for steady-state operation. For inertial fusion, accelerators could compress and ignite fusion targets by ion-beam bombardment and serve as efficient drivers of fusion reactions.

Next-generation reactors, whether based on fission or fusion technologies, require materials that are much more radiation resistant than those used in today's reactors. Accelerators can spur the development of these next-generation materials by producing radiation environments similar to those found in future reactors, providing a platform for materials development that does not currently exist. Accelerators also have a role to play in environmental conservation through their use in processing water and flue gases, already taking place in pilot and industrial-scale plants outside the U.S. As new issues—pharmaceutical contamination of waste and ground water for example—emerge in water treatment, accelerator technologies that destroy contaminants will gain increasing acceptance.

NEEDS, OPPORTUNITIES AND TECHNOLOGIES

Accelerators for power generation and nuclear waste transmutation

Operating nuclear reactors in the United States provide roughly 20 percent of the nation's electricity needs, but supply 70 percent of the nation's emission-free electricity. However, these reactors will generate as much as 100,000 tons of total spent fuel over their lifetimes. Over the past several decades, the U.S. has had difficulty developing a coherent national strategy for dealing with the accompanying waste products.

Accelerators have the potential to affect current nuclear energy technology in three areas: management of spent fuels; provision of sustainable long-term energy sources; and nuclear nonproliferation. It is also conceivable, perhaps even likely, that these factors, coupled with subcritical nuclear energy generation, could enhance public acceptance of accelerator-driven systems compared to standard fission plants.

Management of spent fuels: nuclear waste transmutation

Nearly all risks to future generations arising from long-term disposal of used light-water-reactor nuclear fuel are due to transuranic elements and long-lived fission products, representing roughly two percent of the used nuclear fuel. Unprocessed spent fuel contains materials that require isolation from the environment in safe and stable storage, for hundreds of thousands of years, and so require repositories that rely on geologic characteristics to isolate wastes after containers and barriers fail, after several hundred years. Major uncertainties in planning over such extended periods include climate change, population shifts, ground water transport, geologic stability, and planned or unplanned intrusions.

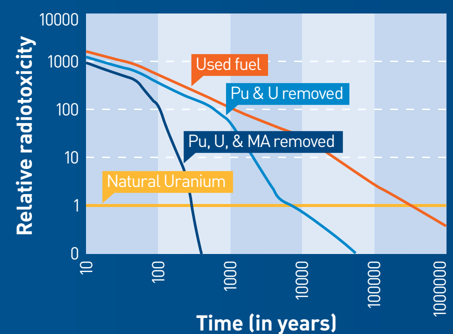
However, removing plutonium and uranium isotopes and the minor actinides from spent nuclear fuel would change the requirements dramatically. Roughly 300,000 years must pass for the spent fuel from a light-water reactor to achieve the level of toxicity characteristic of natural uranium. However, transmuting these isotopes into shorter-lived products would reduce this time to less than 500 years.

Accelerator-driven transmutation would use a high-power proton accelerator to generate neutrons in a dense metal target. Those neutrons interact with surrounding fuel material containing the chemically separated long-lived isotopes, transmuting them into more manageable isotopes. The fuel assembly arrangement ensures that nuclear reactions do not occur without the introduction of an external neutron source produced by the accelerated beam. An accelerator-driven system is subcritical and is ideally suited to burn the most problematic isotopes in spent fuel, the minor actinides and the long-lived fission products.

Either reactors with a fast neutron spectrum or subcritical accelerator-driven systems can achieve the transmutation of the majority of long-lived wastes. Both technologies generate additional useful energy through the burning of the long-lived actinides. It appears unlikely that industry will build sufficient fast reactors in the near term. This affords an opportunity for development of accelerator-based facilities in the interim, providing experience that would allow identification of effective longer-term paths in the future.

Near-term solutions can use a combination of approaches depending on the lifetime of the radioactive isotope. Long-lived fissile isotopes like ^{239}Pu and ^{235}U can be stored with ^{238}U and ^{237}Np for future fabrication into nuclear fuel. Manufactured containers can store short-lived fission products until they safely decay to low radiotoxicity levels in about 500 years. Transmutation and vitrification and burial can provide options for dealing with the long-lived fission products.

An accelerator-driven subcritical system is ideally suited to burn the most problematic isotopes in spent fuel.



Total radiotoxicity of spent fuel relative to the radiotoxicity of natural uranium ore. The top curve represents the waste from a standard light-water reactor. The figure shows that reducing the radiotoxicity of spent fuel to the naturally occurring level takes roughly 300,000 years. Accelerator-driven subcritical systems can dramatically reduce this time. ***Image source: Accelerator-driven Systems (ADS) and Fast Reactors (FR) in Advanced Nuclear Fuel Cycles, A Comparative Study, OECD NUCLEAR ENERGY AGENCY, OECD***

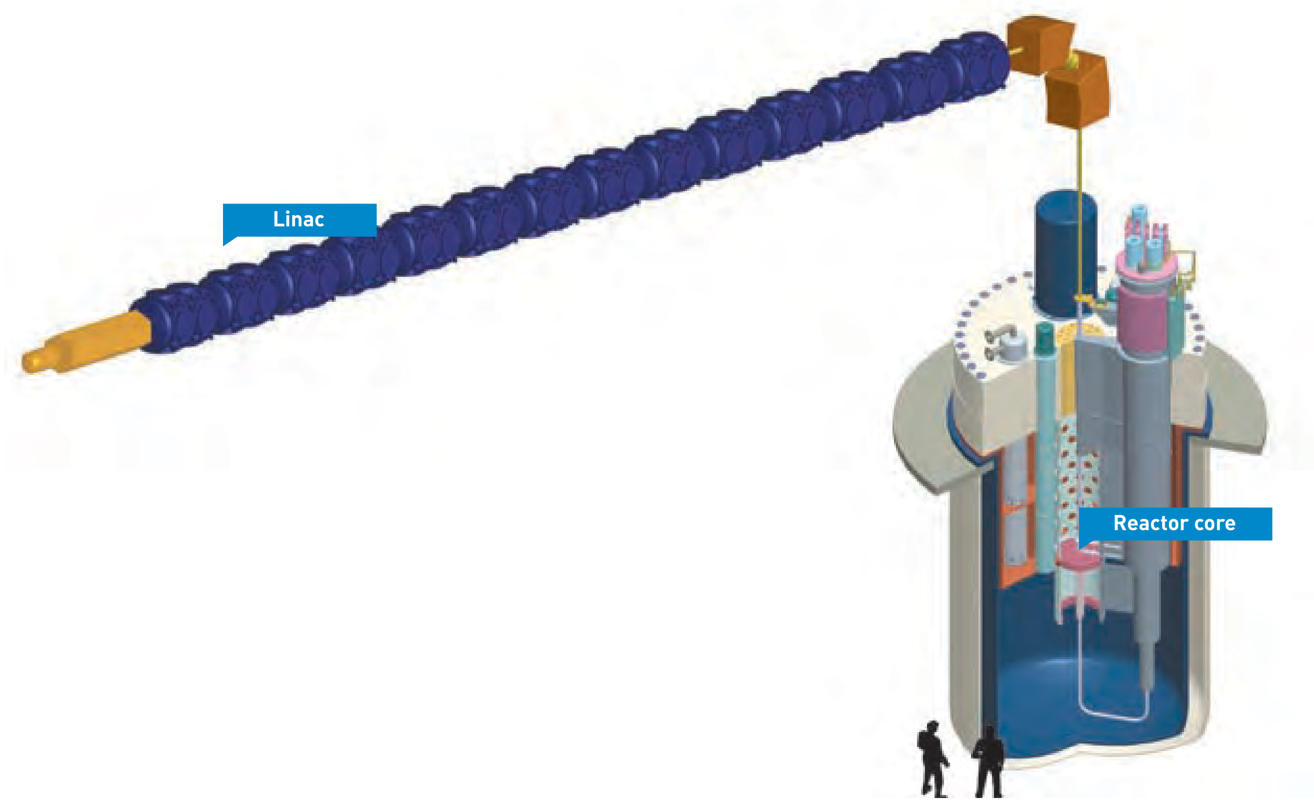
Sustainable energy and nonproliferation: subcritical reactors

A conventional nuclear reactor is based on a controlled fission chain reaction of fissile isotopes, such as ^{239}Pu and ^{235}U. The chain reaction proceeds through the production of multiple neutrons from each fission and the subsequent inducement of more than one fission by each of these neutrons. An alternative approach is to use an external source of neutrons to drive a subcritical reactor loaded with a nonfissile fuel such as thorium (^{232}Th) that cannot support a self-sustaining chain reaction.

Natural thorium, a widely distributed natural resource three to four times as abundant as uranium in the earth's crust, is a potentially valuable fuel for an accelerator-driven subcritical reactor. The thermal power released in a subcritical reaction is typically 100 times the power of the accelerated beam, offering the opportunity for significant energy production. In an accelerator-driven subcritical thorium reactor, the neutrons produced by the proton beam hitting a spallation target breed ^{233}U and promote its fission. Such fission reactions can serve either for power generation or destruction of actinides from the U/Pu fuel cycle. Turning off the accelerator simply and quickly stops the fission reactions.

An accelerator-based thorium reactor has clear advantages: the use of thorium instead of uranium reduces the quantity of actinides produced; the thorium cycle produces only half the amount of long-lived radioactive waste per unit of energy as mainstream light-water reactors; the thorium cycle produces much less plutonium than mainstream light-water reactors, and what it does produce contains three times the proportion of ^{238}Pu, lending it proliferation resistance; the thorium cycle coproduces a highly radioactive isotope, ^{232}U , which provides a high radiation barrier to discourage theft and proliferation of spent fuel; and at today's rate of power consumption there is enough thorium available to sustain such systems for more than ten centuries. Accelerator transmutation will also significantly reduce the impact of minor actinides on long-term radiotoxicity, simplifying repository design, preserving and using the energy-rich component of used nuclear fuel, and reducing proliferation risk.

Concept of an accelerator-driven reactor
Image courtesy of MYRRHA, Belgian Nuclear Research Centre, Mol



Several regions of the world are developing accelerator technologies directly aimed at waste transmutation or energy generation, or both. Major efforts are currently underway in Europe, where MYRRHA, the Multipurpose hYbrid Research Reactor for High-end Applications, has recently been approved, and in Japan, with investment also taking place in both India and China. The U.S., once a leader in this field, has no active program today.

Accelerators for fusion energy

Nuclear fusion is potentially a clean and safe energy source. Two approaches are being developed worldwide: low-pressure/long-confinement-time devices using magnetic field confinement; and very-high-density/short-confinement-time devices using inertial confinement. Accelerator technology plays a key role in both, either as a supporting technology in certain aspects of plasma fusion, or as the central component for ion-beam-driven inertial fusion. Accelerators also play a central role in the development of materials required by both fusion and fission technologies. The need for an intense neutron source to perform accelerated evaluations of materials for fusion power systems motivated fusion scientists to conceive of the International Fusion Materials Irradiation Facility, or IFMIF, and the challenging accelerator technology that supports it.

Magnetic fusion

For magnetically confined plasma fusion reactors such as the International Thermonuclear Experimental Reactor, or ITER, currently under construction in France by an international consortium including the U.S., or the subsequent planned demonstration plant, DEMO, fusion scientists expect ion beams to contribute to the mix of plasma heating techniques. While different schemes can achieve core heating of the plasma, it appears that the plasma current drive required for steady-state operation depends strongly on the high current drive efficiency of ion beams. The ion-beam requirements are quite daunting: tens of amperes of negatively charged ions of about 1 MeV kinetic energy, subsequently neutralized and injected into the plasma.

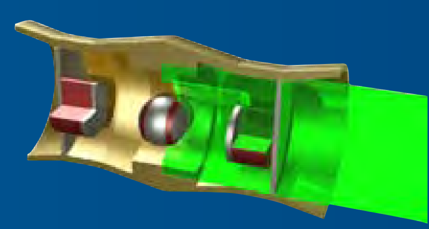
Heavy ion inertial fusion

In heavy ion inertial fusion energy, or IFE, high-energy charged particles from an accelerator heat a small inertial fusion target containing thermonuclear fuel. When compressed, the fuel ignites, releasing energy to generate electricity. Inertial fusion energy has different challenges from magnetic fusion, including the pulsed nature of the energy production, the required high rate of target production and target placement in the reactor chamber, and the reactor-driver interface. In all IFE concepts, the driver and the reactor chamber are separate. Compared to magnetic confinement fusion, this may lead to savings in cost, improved access, ease of maintenance, and reduced concerns for safety and radiation damage and contamination.

Advantages of heavy-ion fusion, identified in past DOE evaluations, still apply. Accelerators have separately exhibited the required performance characteristics to support an IFE facility: total beam energy per pulse of ≥1 megajoule (10^6 Joules); pulse repetition rates of >100 Hz; instantaneous power levels >1 terawatt (10^{12} watt); and sufficient durability. Thick liquid wall-protected target chambers are designed to have 30-year plant lifetimes. These designs are compatible with indirect-drive target illumination geometries, which experiments at the National Ignition Facility at DOE's Lawrence Livermore National Laboratory will test. Thick-liquid protection with molten salt having high thermal and radiation stability has been a standard aspect of most heavy-ion fusion power plant concepts in the past 20 years.

Focusing magnets for ion beams avoid most of the direct line-of-sight damage from target debris, neutron and gamma radiation. Thus, only the final

Accelerator technology has a role to play in the development of fusion energy, either as a supporting technology in plasma fusion, or as the central component for ion-beam-driven inertial fusion.

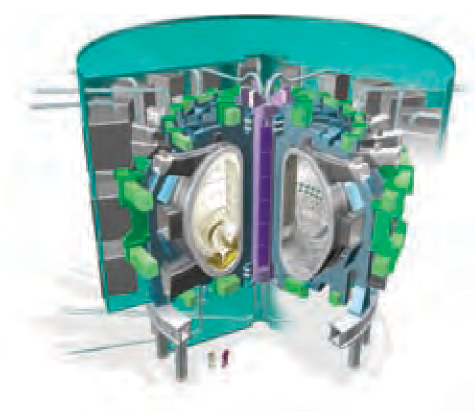


Example heavy-ion fusion target, designed for two-sided illumination by ion beams
Image courtesy of Lawrence Berkeley National Laboratory

focusing magnet coils need to be hardened or shielded from the neutrons. Heavy-ion fusion power plant studies have shown attractive economic and environmental characteristics with low levels of radioactive waste.

Inertial fusion energy accelerator design efforts have converged on multiple heavy-ion beams accelerated by induction linear accelerators. After acceleration to the final ion kinetic energy, the beams, which are nonrelativistic, are compressed axially to the 4-30 nanosecond duration (a few hundred terawatts peak power), required by the target design. Simultaneously they are focused to a few-millimeter spot on the fusion target.

Inertial fusion energy can also potentially address fuel-cycle issues in an expanding role for nuclear energy. The recent Laser Inertial Fusion-Fission Energy initiative is likely to rekindle national interest in high-power accelerators for fission hybrid concepts that combine an ion-driven fusion neutron source with a fission blanket. While serving as a carbon-free energy source, such a scheme has the potential additional benefit of dramatically reducing nuclear waste.

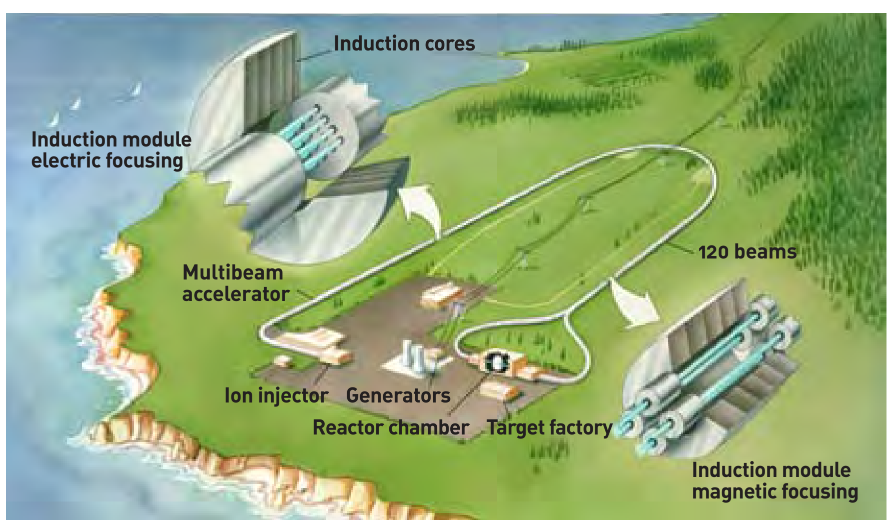


Cutaway of ITER tokamak fusion reactor
Image courtesy of ITER

Accelerators for developing materials for advanced nuclear power systems

Advanced fission and fusion nuclear technologies could deliver significant improvements in sustainability, economics, safety, reliability and proliferation resistance compared to existing nuclear power plants. While these technologies use different nuclear reactions, they have many of the same needs. One common need is for materials and structures capable of functioning reliably for long times in hostile environments with high temperatures, reactive chemicals, high stresses and intense damaging radiation. Such environments represent a significant challenge for materials science, one that will require an intense neutron source for evaluations of the effects of radiation-induced damage to materials.

Worldwide development activities for this application currently comprise two major efforts. The International Fusion Materials Irradiation Facility, or IFMIF, is now in the Engineering Validation and Engineering Design Activities, or EVEDA, stage, carried out within the Broader Approach framework signed by Europe and Japan, but open to all ITER parties. This concept uses the so-called deuterium-lithium stripping reaction, driven by two 40 MeV, 5 megawatt each (10^7 watts in total) deuteron accelerators, to produce intense neutron fluxes. In the U.S., a proposed Materials Test Station at DOE's Los Alamos National Laboratory would use a spallation neutron source driven by the linear accelerator LANSCE with 800 MeV protons for the production of intense neutron fluxes.



Concept of an inertial-fusion power plant based on a heavy-ion induction linear accelerator
Image courtesy of Lawrence Berkeley National Laboratory

ACCELERATORS FOR CLEANER AIR AND WATER

Demonstrations have shown the effectiveness and efficiency of particle-accelerator technology in treating flue gas emissions and polluted water. The use of ionizing radiation to solve environmental problems builds on the numerous studies conducted over the last 50-plus years in radiation chemistry and biology. This research has successfully demonstrated the effectiveness of particle accelerators for purifying drinking water, treating waste water, disinfecting sewage sludge, and high-efficiency removal of NO_x and SO_x from flue gases. Despite this technology's ready availability and its use in other parts of the world, a variety of factors, discussed in this chapter, have stymied its development and adoption in the U.S.

Radiation processing of water via electron-beam irradiation has proved effective for biological and chemical control in water treatment for many applications: drinking water, municipal and industrial waste water, water reuse, ultrapure water for manufacturing, hazardous site remediation of soils and water, and treatment of membrane reject water. Accelerator-based radiation processing has several advantages. The presence of solids does not hinder the destruction of chemicals; solutions that contain highly adsorbing compounds do not decrease the efficacy of the process; and the process requires no chemicals. If the process does not achieve total destruction, in most cases reaction by-products are amenable to biological processes, minimizing treatment costs. Concerns are growing about chemicals, including pharmaceuticals, that conventional treatment processes do not completely remove from water. Such chemicals are targets for treatment by free-radical processes provided by electron-beam irradiation. Nanoparticles also present only recently recognized hazards. For example, nanoparticles appear to be responsible for the fouling of membranes used for water treatment; and as water reuse moves towards membranes this problem is likely to grow. Here again, electron-beam irradiation may offer an alternative to water treatment.

To meet rising worldwide energy demand, projections call for the use of coal to increase by 50 percent by 2030. Beyond the CO_2 problem, coal burning generates large quantities of pollutants that create acid rain and smog, as well as mercury contamination of natural waters including the world's oceans. Pilot plants in Germany, Japan, Korea, Poland and the U.S. have used electron-beam technology developed in the early 1970s for the treatment of flue gas emissions. They showed high efficiency of pollutant removal, up to 90 percent for NO_x and greater than 95 percent for SO_x. Industrial-scale electron-beam-treatment installations are currently in operation in Poland and China. The largest such installation, at the Pomorzany electric power station in Poland, treats approximately 270,000 m^3 of flue gas per hour with a total installed electron processing beam power of 1 megawatt. The by-product is high-quality fertilizer that is sold commercially.

Another potential application is the removal of volatile organic compounds and polycyclic aromatic hydrocarbons, which are products of waste incineration. Recent studies have also demonstrated the potential application of this technology for mercury removal from coal-fired boilers.

Among the most attractive characteristics of electron accelerators for environmental applications is their electrical efficiency. Researchers have measured efficiencies of more than 80 percent, probably the highest of any unit process in a water-treatment train. This translates to the use of less electrical power, an important factor for the water sector, which uses about 20 percent of all the electricity in the U.S.

Research has demonstrated the effectiveness of particle accelerators for purifying drinking water, treating waste water, disinfecting sewage sludge and removing pollutants from flue gases.

Pilot flue-gas treatment plant in Poland
Photo courtesy of A. Chmielewksi, Institute of Nuclear Chemistry and Technology

TECHNICAL AND POLICY CHALLENGES

Electricity usage across the globe. By 2030, world net electricity consumption is projected to increase by 77 percent. ***Photo courtesy of NASA***

Accelerators for generating power and transmuting nuclear waste

The primary accelerator requirements for an accelerator-driven system, or ADS, for either energy production or transmutation of waste are total beam power of 10-30 megawatts, delivered with a beam energy at or above 1 GeV; continuous-wave beam structure; low beam-loss rates of less than 1 watt per meter in the accelerator to allow hands-on maintenance; very high reliability, with fewer than 25-50 unplanned operational interruptions of greater than a minute or two per year; ability to vary beam intensity by a factor of two; beam intensity stability of approximately one percent; accelerator efficiency, defined as beam power divided by total energy drawn from the grid, of greater than 25 percent; and affordability. Counting the associated infrastructure, the cost of the accelerator should be less than about 30 percent of the total system cost.

While a superconducting linear accelerator probably offers the most straightforward approach to ADS, a cyclotron or a fixed-field alternating-gradient, or FFAG, accelerator could also in principle satisfy these requirements. The Accelerator Production of Tritium program at DOE's Los Alamos National Laboratory demonstrated the front-end, key high-power radio-frequency components and halo mitigation studies for a continuous-wave 100 mA proton accelerator, giving confidence that high-current proton accelerators can be built. However, there are no current examples of linacs, cyclotrons, or FFAGs satisfying all the requirements. The high-power cyclotron at the Paul Scherrer Institute in Zurich, Switzerland and the superconducting linac of the Spallation Neutron Source at DOE's Oak Ridge National Laboratory represent the current state of the art. Both facilities operate at slightly greater than 1 megawatt beam power, with PSI at 600 MeV and SNS at 1 GeV. The PSI cyclotron beam is continuous, while the SNS beam is pulsed. Both achieve close to the ADS beam-loss requirements for watts per meter, although not for fractional beam loss. Neither machine's design achieves the ADS reliability requirements, nor were they designed to. FFAGs currently exist as experimental facilities but only with low-energy and low-intensity beams.

Hence, the R&D requirements and their relative priorities for accelerator driven systems are low-fault, high-reliability accelerator designs; beam loss mitigation and beam control for multi-megawatt-class beams; development of low-maintenance and high-redundancy accelerator systems and components; nuclear fuels processing and fabrication optimized for an ADS; integrated system demonstration at relevant system parameters; detailed system trade-off studies (cost, reliability, maintainability); accelerator efficiency; superconducting radio-frequency accelerator cavities and associated technology; high-power accelerator component development; and system-level economic analyses.

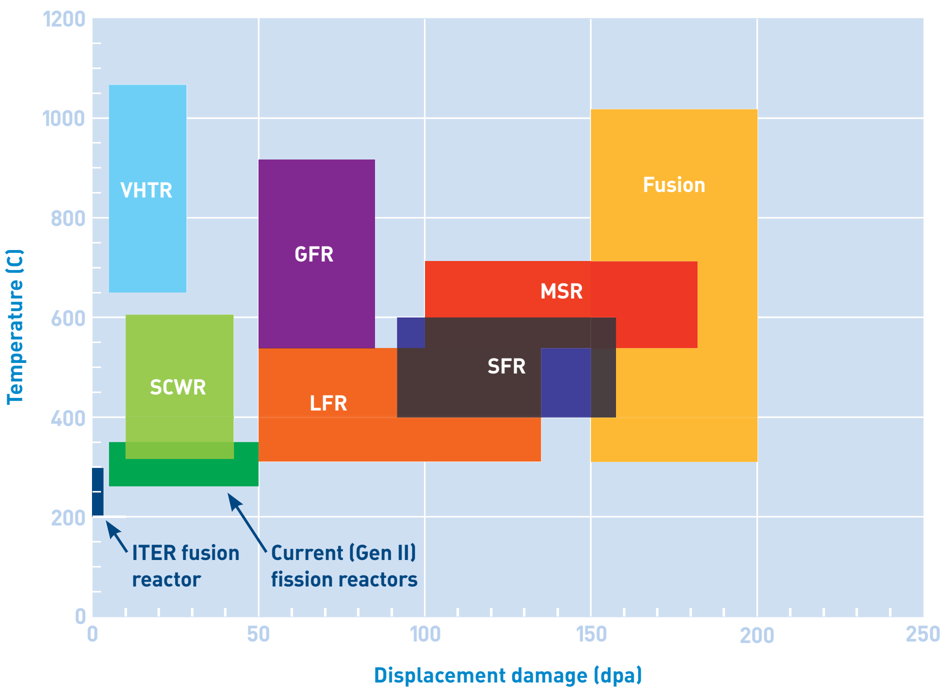
Active research programs outside the U.S., particularly in Europe and Japan, are working toward demonstration-level capabilities. Of note, the EUROTRANS program aims at a demonstration of ADS technology, including the coupling of a high-power accelerator to a subcritical core at the recently approved MYRRHA demonstration facility in Mol, Belgium.

Barriers to deployment, in addition to the technical challenges, include the absence of a constituency for, and consequently little interest in, accelerator-driven systems in the U.S. For advanced fuel cycles, the current emphasis is on a long-term solution based on fast reactors. Some U.S. industrial interests back such approaches, and most assume that the federal government holds responsibility for spent-fuel and proliferation issues. Further barriers to deployment include the multidisciplinary nature of ADS technology—chemical separations technology, reactor technology, accelerator technology—with the consequent lack of a natural champion or owner, or a natural sponsor within DOE or elsewhere. Also blocking progress are the lack of detailed understanding of a sustainable ADS integrated fuel cycle; the perceived costs of accelerators; concern about reliability and about the effects of beam interruption on reactor structural materials; and lack of an operating multi-megawatt continuous-wave proton accelerator with high reliability.

The primary strategy for overcoming these barriers and concerns would be the demonstration of multi-megawatt capability in an accelerator with high reliability, low losses, and high efficiency from the electrical grid to the beam, as well as investigations of the accelerator-subcritical assembly interface. Such a demonstration is synergistic with the requirements of new forefront facilities of interest to several offices within DOE's Office of Science. It would make possible technical evaluations of an integrated system to assess overall performance and comparison with alternatives. Reduced-scale ADS demonstration projects, like those in Europe, could follow. Establishing international collaborations in ADS would cut cost and development time. The formation of public-private partnerships during the advanced R&D and demonstration phases also merits consideration.

Areas where increased investment now would yield the greatest benefit include fundamental physics research in halo development, beam-loss mitigation and control of high-intensity beams; strategies for, and demonstration of, high-reliability operation; development of high-current superconducting radio-frequency systems, cryogenic distribution systems, and high-power radio-frequency sources; research on high-power beam handling and subcritical assembly interface; and optimization of fuel cycle (fuels, materials, recycling) designs to take advantage of an ADS approach.

Establishing international collaborations in accelerator-driven systems would cut cost and development time.



A common theme for fusion and advanced fission is the need to develop high-temperature, radiation-resistant materials. The figure shows operating regions in material temperature and displacement damage (measured in lattice displacements per atom) for current fission reactors and future fission and fusion reactors. Fission reactors include very-high-temperature reactors (VHTR), supercritical water-cooled reactors (SCWR), gas-cooled fast reactors (GFR), lead-cooled fast reactors (LFR), sodium-cooled fast reactors (SFR), and molten-salt reactors (MSR). *Image source: S.J. Zinkle, OECD/NEA Workshop on Structural Materials for Innovative Nuclear Energy Systems, Karlsruhe, Germany, June 2007*

__Many barriers stand in the way of deploying accelerator technology for the study and development of materials for future fission and fusion applications.__

Accelerators and the development of materials for advanced nuclear power

Accelerators for materials irradiation require high-intensity, high-power continuous beams with high availability and low beam losses to allow hands-on maintenance with acceptable radiation exposure. Such accelerators have much in common with those used in other high-power applications, including spallation neutron sources and proton drivers for particle physics research.

Continuous-wave accelerators better simulate the steady-state operation of fission and fusion reactors. Accelerator power must be high enough to produce radiation damage in steel alloys of up to 50 displacements per atom per year. For this application, the accelerator power ranges from 2 megawatts at 1 GeV beam energy for the spallation-based source to 10 megawatts at 40 MeV beam energy for a deuterium-lithium stripping source. To generate enough accumulated radiation damage in a reasonable time, the irradiation facility must operate at least 6000 hours per year, currently beyond the typical availability of existing megawatt-class accelerators. Designers must minimize beam interruptions in order to maintain constant-temperature irradiation conditions. For hands-on maintenance of accelerator beamline components, beam losses in the accelerator must not exceed 1 watt per meter of beamline. Both approaches require the use of technology that is now in the demonstration phase. High-current continuous-wave accelerators are under development, primarily in Europe, for a variety of applications.

The R&D requirements for materials irradiation sources have much in common with other high-power accelerator applications: beam dynamics for low-loss acceleration of high-intensity beams; low-fault, high-reliability accelerator designs; development of low-maintenance and high-redundancy components; development of superconducting radio-frequency cavities and associated technology; and high-power accelerator component development.

Many barriers stand in the way of deploying accelerator technology for the study and development of materials for future fission and fusion applications. First is the requirement for research and development, as well as demonstration. The current activities of the International Fusion Materials Irradiation Facility, or IFMIF, in which the U.S. is not a partner, aim at developing and demonstrating the required technology to produce high-power, low-loss continuous-wave beams suitable for use in a materials irradiation facility. Second, limited funding within the domestic Fusion Energy Sciences community has not provided the capital required to build one. While there is agreement that such a facility would be useful to both the fusion and advanced fission communities, it does not have a natural owner or champion. This points to a third barrier, the need for inter-agency, interoffice and even international cooperation. Finally, such a facility requires particle accelerator technology that is not familiar to either the fission or fusion community.

Overcoming these barriers to deployment will require cooperation among a variety of agencies and offices within the Department of Energy. In particular, DOE's Offices of High Energy Physics, Nuclear Physics, Fusion Energy Sciences, Nuclear Energy and Basic Energy Sciences all may have roles to play in the definition, research, development and exploitation of a materials-irradiation facility. A national materials-irradiation capability would afford an opportunity for synergistic efforts among the various stakeholders. Although the IFMIF effort is open to all ITER signatories, only Europe and Japan presently participate in its activities.

Areas where increased investment now would yield the greatest benefit include modeling and mitigation of high-intensity beam dynamics including beam halo formation; strategies for, and demonstration of, high-reliability accelerator design and operation; and high-current superconducting radio-frequency systems, cryogenic distribution systems, and high-power RF sources.

Cleaner living through electrons

Recent years have brought increasing awareness of the impact human activities have on the environment.

The average global temperature rose one degree Fahrenheit over the past century. Fossil fuel emissions from power plants foul the air and are central to the discussion of global warming. The emissions contribute to dense brown clouds that hang over cities like Los Angeles and Phoenix, triggering asthma and other respiratory problems.

A growing number of scientists believe that particle accelerators could help make the Earth greener by providing a more effective way to clean the air.

For gases from the smokestacks of factories and power plants, the objective is to destroy sulfur dioxides and nitrogen oxides, pollutants that combine with water vapor in the atmosphere and react with sunlight to create acid rain and smog. Conventional treatment typically removes sulfur by scrubbing the flue gas with limestone, a complex process that creates waste water. A separate scrubbing removes nitrogen oxides. Electron-beam technology removes both at once and does not generate any waste.

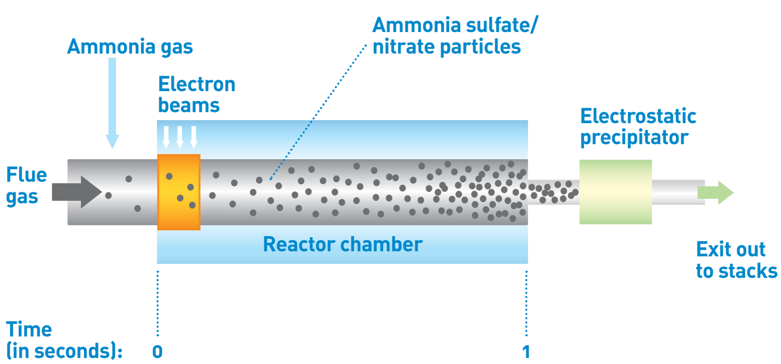
The treatment starts with a conditioning process that cools the flue gas by adding water and ammonia. The conditioned gas streams into a chemical reactor, where it's hit with a beam of electrons accelerated to energies of 800,000 to 1.5 million electronvolts. This triggers chemical reactions that convert sulfur dioxides and nitrogen oxides into ammonium sulfate and ammonium nitrate.

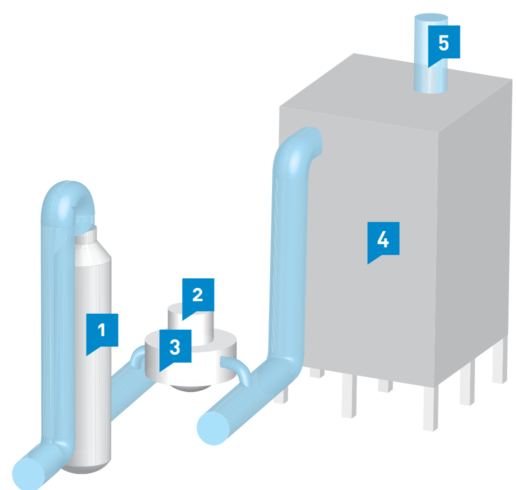
The clean flue gas goes out the chimney; and as a bonus, the ammonium sulfate and ammonium nitrate can be sold as fertilizer.

Pilot plants and operating industrial facilities in Poland have demonstrated that electron-beam technology can remove at least 95 percent of the sulfur dioxides and up to 90 percent of the nitrogen dioxides in flue gases, making them competitive with, if not more efficient than, conventional treatments.

In addition, studies show that large-scale electron-beam flue-gas treatment facilities have cost advantages over conventional plants. "Operation costs can be cheaper by about 15 percent," says Andrzej Chmielewksi, director of the Institute of Nuclear Chemistry and Technology in Warsaw, Poland. "Most importantly, the process creates products that plants can sell later on."

The treatment begins with a conditioning tower (1) that cools the flue gas. The cooled gas moves into an accelerator (2), where an electron beam triggers a chemical reaction (3) to convert the sulfur dioxides and nitrogen oxides into ammonium sulfate and ammonium nitrate. The electrostatic precipitator (4) removes the sulfate and nitrate byproducts and collects them to be sold to fertilizer companies. The clean gas goes out the chimney stack (5). *Image source: PAVAC Industries; image: Sandbox Studio*





Inspection of a superconducting radio-frequency cavity *Photo: Reidar Hahn, Fermilab*

Bridging the gap between accelerator systems research and environmental applications calls for a joint venture of universities, accelerator manufacturers, industrial water and power users, and DOE and other mission agencies.

Accelerators for inertial confinement fusion energy

An R&D effort culminating in a credible, integrated design for a heavy-ion-fusion-based prototype for pure fusion (or hybrid fusion and fission) would focus on accelerator physics R&D, including experiments of modest scale. The near-term objective of the program would be the engineering design of two facilities. The first is a prototype experimental facility for fusion target experiments integrated with all key ion-beam manipulations. Concepts for an experimental facility developed several years ago with similar goals should be revisited in light of developments since then. The next step would be a demonstration power plant design. Based on these objectives, several cross-cutting accelerator and beam physics research topics merit further study: high-brightness heavy-ion injectors, which must deliver approximately 1 ampere current (if singly ionized); reliable, high-field transverse focusing lenses; solenoid magnets, magnetic quadrupoles and electrostatic quadrupoles; induction accelerator module design; electron clouds and beam background-gas interactions; axial beam compression and methods to compensate or correct for chromatic aberrations; and beam-plasma instabilities.

Two barriers to deployment are notable. First, no one has yet achieved the ignition and demonstration of significant gain of an inertial-fusion-energy relevant target. The National Ignition Campaign, NIC, at DOE's Lawrence Livermore National Laboratory may accomplish this soon. The first experiments at NIC will use indirect-drive targets and thus are relevant to heavy-ion-driven fusion. Second, an integrated experimental facility capable of heavy-ion fusion relevant target-heating experiments may cost several hundred million dollars. However, this would be the most significant step leading to a fusion engineering test facility including reactor chamber, fuel and power management. An important step to overcoming these barriers would be to encourage funding agencies that are potential stewardship partners, but that presently do not collaborate in this area, to join forces. Expanded international collaboration is also desirable.

Topical solicitations of Small Business Innovation Research/Small Business Technology Transfer proposals would help bridge the gap between basic accelerator R&D and commercial technology deployment of accelerators for heavy-ion fusion. Increased investment would yield high benefit in areas that are cross cutting with other accelerator applications that also require high-intensity beams (for example, high-brightness ion injectors, beam loss, halo and mitigation), and component R&D (for example, superconducting materials and magnets).

Accelerators for cleaner air and water

Accelerators for treating flue gas need ~0.8 MeV beam energy and ~1 megawatt total installed electron beam power per 100-megawatt plant. For use in water treatment, the beam energy is less than 5 MeV, with beam power ranging from 0.4 megawatts for a small plant to 20 megawatts for a large water-treatment plant. Many accelerators used in industry for radiation processing routinely achieve the required accelerating potentials; the major challenges in accelerator designs are to provide higher beam power and to increase reliability to industrial levels. The accelerator capability largely exists today in private industry; the existing electron-beam industry can best do further development.

The U.S. lags behind the rest of the world in pilot and demonstration projects. Flue-gas-treatment pilot plants exist or are under development in Poland, Bulgaria and China, and an industrial-scale water treatment facility operates in Korea. International collaboration would reduce time to market for U.S. accelerators. Again, there is an opportunity for interdepartmental and interoffice cooperation, as well as for public-private partnerships.

Although the potential environmental market for accelerators is large, it suffers from fragmentation, risk aversion, the perception that high voltage implies excessive energy costs, and a volatile regulatory framework. Initial market entry attempts encountered what has come to be known as "the valley of death." Although capital existed for developing ideas and proof of concept, funding for the first plants was unavailable. There was therefore no opportunity to conduct long-term reliability studies, develop economic analyses, and train practitioners in the new process.

Bridging the gap between accelerator systems research and environmental applications calls for a center, a joint venture of universities, accelerator manufacturers, industrial water and power users, and DOE. Other mission agencies, including the Environmental Protection Agency and possibly the Departments of Defense and Homeland Security, might benefit from joining in the formation of this center. Outreach, education and training would be an integral part of this center at full-scale demonstration plants.

FINDINGS

There are many fertile areas of opportunity for accelerator-based solutions to national energy and environmental challenges:

- Accelerator-driven subcritical reactors, accelerator-driven transmutation of waste, and inertial confinement fusion for safe, sustainable energy sources, manageable activated waste, proliferation control, and reduced carbon footprints
- High-power hadron accelerators to validate materials for use in advanced nuclear systems
- Low-energy, high-power electron accelerators for clean air and water

The U.S. lags behind the larger international community in research and development for accelerator applications for energy and the environment.

Accelerator facilities for energy and environmental applications require the following common features, all of them beyond current capabilities: accelerator reliability above levels typically found in physics research facilities; beam-loss control and mitigation to maintain beam losses at less than 1 watt per meter; and multi-megawatt proton sources featuring efficient low-energy acceleration with high beam quality.

Overcoming current barriers to deployment will require economic modeling to establish cost effectiveness of accelerator-based systems; industrial buy-in; interagency, interoffice and international cooperation; and programs to bridge the gap between advanced development and industrial adoption of technologies.

Many of the findings that apply to the use of accelerator technology in energy and the environment apply broadly to applications in industry, medicine, security and discovery science. The development of high-intensity, high-efficiency, low-loss sources of particle beams would find wide application. Investment in understanding beam dynamics associated with low-loss acceleration up to about 100 MeV, and the further development of acceleration systems based on superconducting radio-frequency technologies would greatly encourage such applications. Investment would include both computer simulations and technology demonstrations. Effective development in these areas, to the benefit of multiple constituencies, will require enhanced interagency and international cooperation, as well as vigorous programs to bridge the gap between advanced development and industrial deployment of these technologies.

Many of the findings that apply to the use of accelerator technology in energy and the environment apply broadly to applications in industry, medicine, security and discovery science.

Accelerators for Medicine

In 1930 at Berkeley, Ernest O. Lawrence invented the cyclotron, the first circular accelerator. Lawrence often operated the early cyclotrons throughout the night to produce medical isotopes for research and treatment. From the earliest days of accelerator physics in the 1930s, the bold and innovative technologies of particle accelerators have created powerful tools for medicine.

Today, accelerator technologies are critical to many vital medical applications. Tens of millions of patients receive accelerator-based diagnoses and therapy each year in hospitals and clinics around the world. Hundreds of research projects and clinical trials are underway, aimed at developing more advanced medical applications of accelerator technology. At the same time, research at accelerator-based light and neutron sources is unraveling the complex structures and functions of biological systems, leading to a better understanding of these systems and to development of new pharmaceuticals.

Government-funded laboratories and research institutions have played key roles in developing the accelerator technologies for most of these applications. Stanford University and the Department of Energy's Los Alamos National Laboratory helped develop linear accelerators for electrons, now the workhorses of external-beam therapy. The DOE's Oak Ridge and Brookhaven National Laboratories contributed much of the present expertise in isotopes for diagnosis and therapy. Lawrence Berkeley National Laboratory pioneered the use of protons, alpha particles (helium nuclei) and other light ions for therapy and radiobiology. Private-sector funding has also played an important part, notably in the successful commercialization of electron linacs by Varian, Inc., and in developments for proton therapy by the Massachusetts General Hospital. In an early example of a public-private partnership, DOE's Fermi National Accelerator Laboratory built and commissioned the first hospital-based proton synchrotron for the proton therapy facility at Loma Linda University Medical Center in 1990.

Tens of millions of patients receive accelerator-based diagnoses and treatment each year in hospitals and clinics around the world.
Photo: Marissa Roth,* The New York Times*/Redux

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A careful look at government policies that affect development of accelerator-based medical technology could overcome roadblocks to progress in re-establishing U.S. laboratories and industries as global leaders in the field.

In the United States today, the commercial sector provides all electron linacs for x-ray therapy, the most widely employed therapy, with primary vendors from the U.S., Europe, Japan and China. Industry now also provides proton and heavier ion-beam therapy facilities, with cyclotron- or synchrotron-based systems. All of these systems come from European or Japanese sources. U.S. industry participation in this market has been quite limited.

Maximizing the efficacy of proton and ion beam therapy still calls for many technical innovations. The U.S. led the way in the early days of accelerator development, but the momentum for these technical developments has gone overseas. The U.S. has the resources to regain leadership in this field, but it will require a focused and sustained effort to achieve this goal.

Resources at federally funded national laboratories and universities can provide expertise for breakthroughs in accelerator technology and beam-delivery systems. However, mobilizing these resources will require public funding and engaging the U.S. private sector for commercialization, involving the development of new models for public-private partnerships.

A careful look at government policies that affect development of accelerator-based medical technology could overcome roadblocks to progress in re-establishing U.S. laboratories and industries as global leaders in the field. Public-private partnerships offer great opportunities for development. There are some notable successes, but in general the U.S. lags behind international progress in such partnerships in these areas, hampered by legal restrictions, risk aversion within the funding agencies and in industry, and by intellectual property issues.

This chapter focuses on two of the principal medical applications of accelerators: their role in the production of radioisotopes for medical diagnosis and therapy, and as sources of beams of electrons, protons and heavier charged particles for medical treatment. A sidebar highlights the role played by accelerator-based light and neutron sources in elucidating the structure and function of complex biological systems and the development of advanced pharmaceuticals.

Radioisotopes

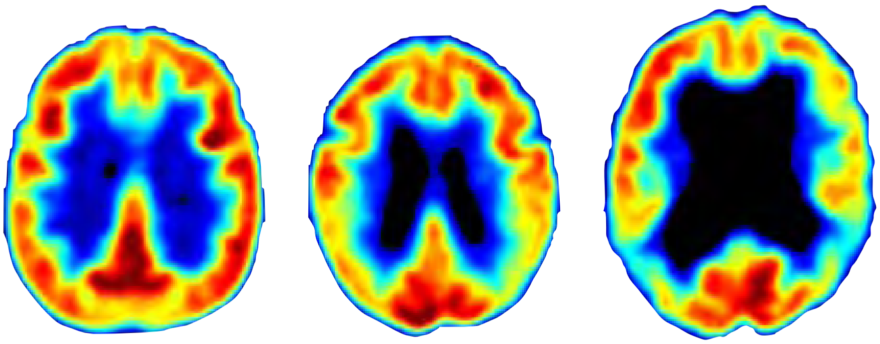
Radioisotopes have become vital components for scientific research and industry, with hundreds of applications in medicine, biology, physics, chemistry, agriculture, national security and environmental and materials science. Perhaps the most directly beneficial occur in medical diagnosis and therapy. Building on pioneering efforts at the DOE laboratories, isotopes have improved the diagnosis and treatment of disease and changed the quality of life for millions of patients.

The wide range of half-lives of radioisotopes and their differing radiation types allow optimization for specific applications. Isotopes emitting x-rays, gamma rays or positrons can serve as diagnostic probes, with instruments located outside the patient to image radiation distribution and thus the biological structures and fluid motion or constriction (blood flow, for example). Emitters of β rays (electrons) and α particles (helium nuclei) deposit most of their energy close to the site of the emitting nucleus and serve as therapeutic agents to destroy cancerous tissue.

The ability to attach a radionuclide to a pharmaceutical agent for transport of the isotope to the desired site is key to its effectiveness. Researchers have achieved considerable success in this area. For example, fluorodeoxyglucose, or FDG, serves as a carrier for the positron emitter ^{18}F to sites of high metabolic activity. Positron-emission tomography cameras, or PET scans, can produce detailed maps of active areas in the brain and other organs. Technecium-99m has now become the workhorse of diagnostic nuclear medicine, with over 50,000 procedures performed each day in the U.S. Therapeutic applications can also use radiopharmaceuticals as delivery agents (for α emitters such as ^{211}At), or can take the form of metallic "seeds" containing β-emitting isotopes such as ^{90}Sr, ^{103}Pd, ^{192}Ir, or others that are surgically implanted into a tumor, a procedure widely used now for prostate treatments.

The half-life of an isotope must be long enough to allow transport from production sites to end-use locations without excessive loss, and short enough to minimize the unwanted radiation dose to the patient after the procedure is complete. The use of "generators," such as $^{99}Mo/^{99m}Tc$, involves a longer-lived parent (2.75-day ^{99}Mo) that decays to a shorter-lived daughter (6-hour ^{99m}Tc). Specialized reactors produce the ^{99}Mo as a fission fragment for transport to end-use sites, where clinicians "milk" the ^{99m}Tc daughter from the generator as needed for diagnostic procedures.

Bone scans locating cancerous growth by indicating increased uptake of radioactive ^{99m}Tc *Image courtesy of the "Workshop on the Nation's Needs for Isotopes: Present and Future (2008)"*



Normal **Mild cognitive impairment** **Alzheimer's disease**

Positron emission tomography (PET) images showing reduced glucose metabolism in temporal and parietal regions of the brain in Alzheimer's disease and mild cognitive impairment
Image courtesy of S. Baker, W. Jagust and S. Landau

2

In the U.S. alone, 15 million medical procedures per year use ^{99}Mo/^{99m}Tc.

Radioisotope production today

Sources of isotopes are either reactors or accelerators of varying sizes. The accelerator-induced nuclear reaction used to produce a specific isotope has an optimum beam energy and beam species, most often protons at energies from 10 MeV to a few hundreds of MeV, but also helium and other light nuclei. ^{99}Mo is a fission fragment that is today produced using highly enriched uranium, or HEU, targets and in reactors with HEU cores. There is no current U.S. commercial production of ^{99}Mo.

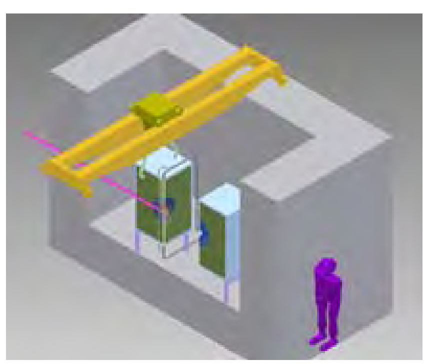
Small cyclotrons at energies below 15 MeV can easily produce many of the short-lived light PET isotopes, for example ^{18}F with a 110-minute half-life. The most advanced of these machines is a self-shielded unit capable of completely automated operation yielding labeled fluorodeoxyglucose delivered to a researcher. These units are commercially available, compact and affordable for hospitals and diagnostic centers. Approximately 300 are currently deployed in the U.S.

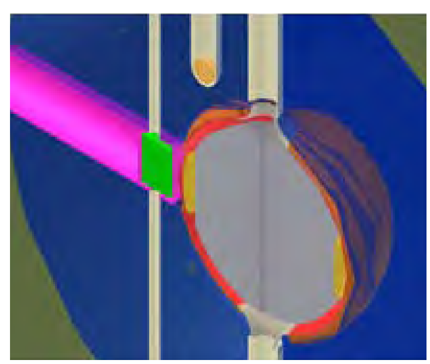
Larger cyclotrons of 30 to 40 MeV are also commercially available, and form the supply backbone for several other clinically useful longer-lived isotopes such as ^{201}Tl, ^{123}I, ^{67}Ga, ^{103}Pd, as well as for a number of research isotopes.

Radioisotopes produced at higher energies are available through the DOE Isotope Program from satellite beams at DOE's Brookhaven (200 MeV protons) and Los Alamos (100 MeV protons) National Laboratories using large accelerator complexes with primary missions in other fields. These facilities are the primary sources for several commercial isotopes (e.g. ^{68}Ge, ^{82}Sr) requiring the higher energy beams, and for interesting research isotopes such as ^{67}Cu. Still higher energies would be desirable for production of isotopes of value for biological and medical research, such as ^{32}Si and ^{26}Al, now accessible in useful quantities only with higher energy beams.

Currently, the field faces two major challenges: i) uncertainties in continuous access to radioisotopes for medical research. Many are short-lived and much of the current production relies on accelerators and reactors whose primary mission is not isotope production; ii) a tenuous supply chain for clinically relevant fission-produced radioisotopes such as ^{99}Mo/^{99m}Tc. Presently, ^{99}Mo/^{99m}Tc is only available from foreign sources that have experienced major unplanned supply interruptions over the past few years.

The national isotope program has long operated as a dispersed entity of DOE and its predecessor agencies. In 2009 the Isotope Production Program was transferred to DOE's Office of Nuclear Physics, or ONP, as the Isotope Development and Production for Research and Applications Program, with the following key missions: i) to produce and sell radioisotopes and related isotope services; ii) to maintain the necessary infrastructure; iii) to conduct R&D on new and improved production and processing techniques. The main radioisotope





Target station and cutaway view of a neutron amplifier target for production of isotopes in a superconducting radio-frequency-based accelerator facility ***Images courtesy of J. Nolen, Argonne National Laboratory***

currently used in medical diagnostics, $^{99}Mo/^{99m}Tc$, is not under the ONP isotope program. This is in part due to non-proliferation concerns surrounding current reactor-based production of $^{99}Mo/^{99m}Tc$ using highly-enriched uranium.

The Office of Nuclear Physics charged the Nuclear Science Advisory Committee, or NSAC, to establish a standing isotope sub-committee to advise on the isotope program. A comprehensive report and recommendations are now available. Four initiatives are included in the context of an optimum budget scenario: i) the proof-of-principle demonstration of increased production of alpha-emitting radioisotopes for therapy; ii) a new electromagnetic isotope separator facility; iii) a new 30-40MeV variable-energy, multiple-particle, high-current accelerator facility; iv) for the longer-term, the start of a future initiative able to address a significant increase in demand as research opportunities expand into general use. The nature and cost of such a facility is expected to depend on the evolution of future opportunities and the response of the private sector to commercial radioisotope production. The third initiative would likely involve a commercially available cyclotron.

In parallel, DOE's National Nuclear Security Administration, or NNSA, with responsibility for $^{99}Mo/^{99m}Tc$ has issued a call for proposals for the development of new approaches to $^{99}Mo/^{99m}Tc$ production, including accelerator-based facilities. Recently a number of promising new concepts have emerged for isotope production addressing important needs for alpha-decaying isotopes and fission produced isotopes such as ^{99}Mo. They suggest that a very flexible accelerator, or ideally more than one, with variable beam species, could meet the demand for production of a broad array of research radionuclides. The complex should have multiple target stations, and cells for target processing and production of end-use materials. Such a facility seems uniquely suited to meet the challenge of the fourth initiative, above, and would meet a critical need.

There is currently substantial activity toward radioisotope production, including a congressional bill in preparation regarding government support. In the context of the present report we limit ourselves to future opportunities and advances that accelerator research and development can provide.

NEEDS, OPPORTUNITIES AND TECHNOLOGIES

The development of a nuclear-medicine procedure follows a well-defined process. Initially, researchers select a promising isotope for investigatory studies. They develop the chemical attachment to a suitable carrier molecule. They then carry out cellular-level studies, animal studies and eventually limited patient trials. A critical element of such a program is the availability of a continuous supply of the isotope in sufficient quantities to conduct studies, usually over a period of several years. After successful research come large-scale clinical trials. A key factor is to establish and maintain a reliable supply chain for the isotope. For clinical trials, the isotope requirements are up to several orders of magnitude greater than for the research stages, and the isotope must be available on demand 12 months of the year. These requirements present a significant challenge for production facilities to cover the production and operation costs of this increasing demand with the accompanying risk that clinical trails may not ultimately be successful. However, once radioisotopes are in routine clinical use and in much higher demand, private industry can usually be counted on to develop the production and distribution capabilities.

In the U.S. alone, 15 million procedures per year use ^{99m}Tc. The current world supply of $^{99}Mo/^{99m}Tc$ depends primarily on three aging reactors, one in Canada and two in Europe. The Canadian reactor is currently offline and at least one of the European reactors faces significant maintenance issues. Many feel that the supply of $^{99}Mo/^{99m}Tc$ is in serious jeopardy. While emerging short-term plans may avert a serious shortfall, the crisis clearly needs a long-range solution. Accelerators can play a pivotal role.

Isotopes have improved the diagnosis and treatment of disease and changed the quality of life for millions of patients.

Assembly of a superconducting accelerator section for production of ion beams
Photo courtesy of J. Nolen, Argonne National Laboratory

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Major advances in high-power particle accelerators and high-power target technologies now offer significant opportunities in the production of isotopes via spallation-induced neutron irradiation. For example, 100 kW of 200-MeV protons bombarding a depleted uranium target produces copious amounts of neutrons for transport to an efficiently designed low-enrichment uranium blanket. This system would produce enough ^{99}Mo to satisfy the current U.S. demand. Such a facility would address the proliferation concerns inherent in the use of highly enriched uranium targets at reactors.

The accelerator and target technology at this beam-power level is well understood. Indeed, one major advantage of this production system is that superconducting linear accelerator technology capable of 20 times this beam power is now available, and could use rapid-switching techniques to distribute the beam simultaneously to many target stations. Such an accelerator facility could supply future projected demands for ^{99}Mo, in a form useable with current FDA-approved generator technology, as well as therapeutically relevant β and α emitters when clinical trials demonstrate their efficacy. It could also serve the needs described above for producing new research isotopes.

Electron-beam-based accelerator technologies also show promise for radionuclide production, either via photo-nuclear reactions with megawatt-class beams, or using Compton backscatter of high-intensity laser beams with high-quality light source beams. These promising technologies deserve support and encouragement for possible effective applications for radionuclide production as well as for other fields.

A high-power accelerator facility could provide a reliable source of neutron-produced isotopes such as ^{99}Mo, and also have sufficient power and flexibility to supply a steady stream of research isotopes.

TECHNICAL AND POLICY CHALLENGES

A high-power accelerator facility could provide a reliable source of neutron-produced isotopes such as ^{99}Mo, and also have sufficient power and flexibility to supply a steady stream of research isotopes. While such a facility is within technical reach, ensuring well-engineered, reliable structures to perform this mission would still require substantial development and demonstration.

Specific areas that would require R&D for a proton facility are target design; efficient and lossless beam-switching techniques to service several target stations; low- and medium-velocity superconducting cavities; radio-frequency systems and controls; ion sources for high-brightness beams of protons and light ions; control systems for real-time acceleration of multiple beams with independent intensity, energy and perhaps species; instrumentation for monitoring these high-intensity beams; and beam dynamics for high-current linacs to characterize possible halo and beam-loss mechanisms.

This technology shares many research goals with research at U.S. national laboratories, including superconducting cavity research at DOE's Thomas Jefferson National Accelerator Facility, at Argonne National Laboratory with its ATLAS facility, and at Fermi National Accelerator Laboratory with its high-intensity upgrade initiatives. The DOE's Brookhaven, Oak Ridge and Lawrence Berkeley National Laboratories also have relevant programs.

While resources at DOE laboratories would be valuable, in fact essential, to the successful development of such a facility, partnership with the private sector would be an extremely important element. The private sector alone would be unlikely to invest in this facility, considering the high cost and small revenue stream expected during the research phases and the uncertain ultimate return on its investments. The same situation does not exist in other parts of the world. Two effective public-private partnerships, Nordion/TRIUMF in Canada and ARRONAX in France, offer models for addressing this issue. While both include revenue-producing production arms, the partners share the risks for research-isotope development and make available adequate resources for carrying these research programs to logical conclusions. Applying such models, or perhaps improving on them, could have relevance for the U.S.

Accelerator-based facilities for pharmaceutical development

New and powerful accelerator-driven synchrotron radiation and neutron-beam facilities provide opportunities for commercial and industrial applications in many areas of science and technology. Pharmaceutical research and the study of complex molecules offer two prime examples in medicine and biology.

Synchrotron radiation for drug development has become a significant research and development tool at current-generation light sources. Studies range from research in drug discovery, where protein crystallography is a uniquely useful tool in structure-based drug design, to research related to later stages of the drug development cycle, where structural studies and other techniques support the transition from a "compound of interest" to a drug.

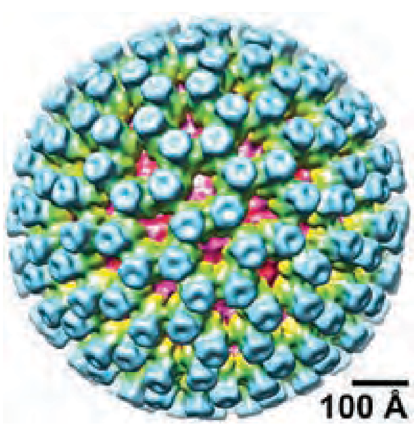
Spallation neutron sources produce high-quality thermal and epithermal neutron beams that are extremely effective in imaging soft tissue. Researchers also use them to unravel the role of hydrogen and water in macromolecular structures and complex fluids, such as blood; or in soft-tissue environments including cell walls and other permeable membranes.

The drug development cycle involves many steps. Of several million candidates, only one or two result in effective drugs, after a development period of some 15 years. X-ray techniques are crucial to many of the steps in the cycle. In detailed structural crystallography studies available at synchrotrons, for example, researchers use high-intensity radiation to assess dynamical effects such as transitions during hydration or dehydration that occur over short periods. They use similar techniques to make *in situ* measurements of the crystallization of amorphous solids.

Pharmaceutical developers also use intense synchrotron radiation applied simultaneously to small- and wide-angle x-ray scattering to study nanostructure features of samples. These techniques illuminate the characteristics of the different components of pharmaceutical formulations. They make possible measurements with submillisecond time scales, allowing real-time study of the relevant structural changes during processing. These studies are essential for understanding the stability and delivery of drugs. The large investments by drug developers at synchrotron radiation sources point to the significance of these accelerator-based facilities to pharmaceutical research and commercial drug development.

In the left image, the distinctive architecture of the surface of the rotavirus, a deadly gastrointestinal virus that annually kills more than half a million children worldwide. Research at a DOE light source has revealed details of the molecular structure of the surface protein, showing how an antibody neutralizes the virus and potentially leading to an effective rotavirus vaccine. *Image courtesy of the Proceedings of the U.S. National Academy of Sciences*

In the right image, the structure of a glutamate receptor, a fiendishly complicated protein that mediates signaling between neurons in the brain and in the nervous system. Researchers used two DOE light sources to map the protein, also thought to be crucial to memory and learning. Knowledge about the receptor may lead to new drugs and treatments for a range of neurological disorders. *Image courtesy of* Nature *magazine*



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Maximizing the dose to tumor tissue while minimizing the dose to surrounding normal tissue is a key objective of radiation therapy.

Beam therapy

Radiation therapy by external beams has developed into a highly effective method for treating cancer patients. Cancer is the second-largest cause of death in the U.S. More than one million new cases are diagnosed every year, and about half receive radiation either as their primary treatment or in conjunction with chemotherapy, surgery or other modalities.

The vast majority of these irradiations are now performed with microwave linacs producing electron beams and x-rays. Accelerator technology, diagnostics, and treatment technique developments over the past 50 years have dramatically improved clinical outcomes. Recent decades have seen the evolution of particle beam therapy using proton and carbon ion beams and to a lesser extent helium and neon ions. The number of centers offering particle-beam treatments is growing rapidly. Today, 30 proton and three carbon-ion-beam treatment centers are in operation worldwide, with many new centers under construction or in the active planning stage. The technology and medical expertise for particle-beam therapy is continuously and rapidly developing, with major advances virtually certain in the coming years.

X-ray therapy

The most widely employed radiation treatment uses high-energy photons, commonly referred to as x-rays, produced by an electron beam striking a heavy-metal target. S-band electron linacs of 5-30 MeV are the mainstay of radiation therapy, with about 5000 in operation worldwide. Powered by either a magnetron for lower-energy, or a klystron for higher-energy electrons, these accelerators produce sharp beam pulses at repetition rates up to 1000 Hertz.

This technology is a highly successful spinoff from research programs in particle and nuclear physics of the 1950s. The low rigidity of the electron beams and very efficient packing of the accelerator and beam-transport system has reduced overall device lengths to one or two meters. Their compactness, efficiency, reliability and moderate cost have factored heavily into their acceptance for clinical applications. In addition, the isocentric gantry, which allows rotation of the full instrument around the patient, provides for multiple treatment directions, with the patient remaining in the optimal position for treatment, namely supine, as it is the most comfortable, provides the least patient movement during irradiation, and matches imaging technology.

A modern electron-accelerator-based x-ray facility *Image courtesy of Varian Medical Systems of Palo Alto, California*

The x-ray depth-dose relation inside a patient is basically exponential, after dose build-up in the superficial 1-3 cm. Hence, treating a deep-seated tumor involves significant doses superficial to and downstream of the defined target volume. High dose levels to nontarget normal tissues can be reduced by multiport treatments, where beams are brought in from several directions and overlap at the tumor, and by the use of sophisticated collimators to restrict the beam cross section to the different shape projections of the tumor along each beam path. Advanced techniques such as intensity modulated radiation therapy, or IMRT, can achieve good conformation of the delivered dose to the defined target volume. However, the entrance and exit doses for each of the large number of beam paths result in a radiation "dose bath" delivered to large volumes of normal tissue outside the target volume. This dose and dose distribution contribute to an increased risk of serious long-term radiation injuries.

Particle beam therapy

Robert R. Wilson, Fermilab's founder, writing in the medical journal Radiology in 1946, observed that beams of protons and heavier ions would be ideally suited to treat cancer patients because the stopping characteristics of these particles mean that most of the energy deposition and hence biological damage occurs very close to the end of the particles' range—at the so-called Bragg peak. Stopping the beam inside the tumor would substantially enhance the dose delivered to the tumor, while keeping the dose to normal tissue along the entrance path to a minimum. Furthermore, because the particles stop in the tumor, there is in essence no exit dose. Because maximizing the dose to tumor tissue while minimizing the dose to surrounding normal tissue is a key objective of radiation therapy, charged particle beams have an intrinsic physical advantage over photons.

Progressing from Wilson's suggestion to development of particle beams as an effective tool in the war on cancer has been a highly complex journey occupying the better part of 50 years. Starting with the use of research accelerators originally dedicated to nuclear and particle physics as sources of high-energy beams, the field has now progressed to the point where hospital-based accelerator facilities deliver very sophisticated treatments. Radiation oncologists use the complex array of imaging technology—Computer Tomography, Magnetic Resonance Imaging, Positron Emission Tomography and others—to define and localize the target and critical nontarget tissues. Applied physicists have developed complex computer-based treatment plans that now or in the very near future will include motion-compensated three-dimensional plans incorporating simulated dose calculations. Radiobiologists have studied in detail the response of organs and tissues to irradiation with ions from protons to carbon and beyond. Radiation oncologists and their medical teams have integrated all of this information to develop patient management strategies and conduct clinical studies to assess the efficacy of the particle beams.

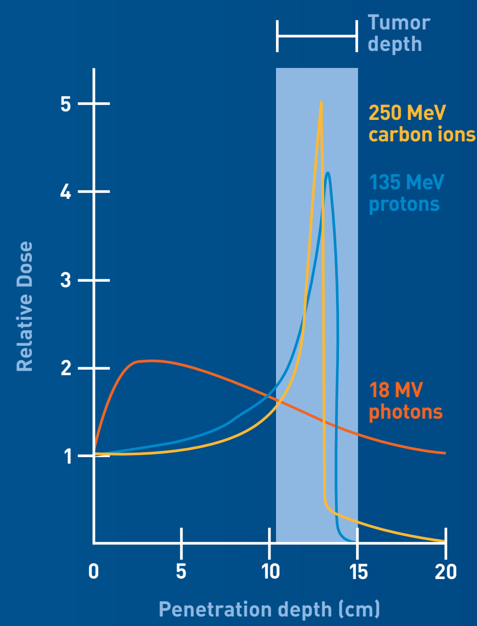
Treatments require careful tailoring of the distribution and energy of the beam, to cover as closely as possible the target volume with the prescribed flux of particles. Thickness of the treatment volume requires stopping particles at different depths. Depth modulation is done by changing the energy of the beam, either at the accelerator or by degrading systems in the transport line. Collimators, either computerized "multi-leaf" collimators or collimators made from heavy metals, control the lateral margins of the treatment field. The most sophisticated delivery systems rely on scanning with fast magnets, sweeping the beam over the treatment volume and modulating the profile at each depth (beam energy) to meet the prescribed dose and shape. All these beam delivery systems have reached a good level of maturity, adequate for safe delivery of radiation to patients. However, the field agrees on the need for substantial improvement in technology, as well as in understanding of the underlying biology and clinical factors.

Ions heavier than protons have attracted interest, for one, because of sharper edges to treatment fields, owing to the higher momentum of the ions and less spreading through multiple scattering. As a result, normal tissues near the tumor receive a smaller energy dose, a clear physical dose distribution advantage of the heavier-ion beams. In addition, the higher ionization density or "high LET" (linear energy transfer) of the heavier particles can cause greater cell damage to tumor tissue and affect repair probability. There is a very low-dose "fragmentation tail," in which nuclear reactions of the heavier projectile produce lighter fragments that deposit dose beyond the stopping point. This yields an exit dose that is not present with protons.

The field of particle-beam therapy today is still very much in evolution but has made tremendous strides in bringing the Bragg peak into clinical use in hospitals. More than 70,000 patients have received treatments, predominantly with protons but also with heavier ions, in particular carbon.

Even with less than fully optimized treatment techniques, clinical experience with these ions has produced very impressive local control rates for a broad range of tumor sites. Specific examples for protons include malignant melanoma of the eye (95 percent remission at 15-year follow-up); chondrosarcoma of the

The field today has made tremendous strides in bringing the Bragg peak into clinical use in hospitals.



Energy deposition (dose) of photon, proton and carbon as a function of penetration depth in tissue. The Bragg peak for the ions and protons indicates that the highest energy deposition occurs at the particles' stopping point. Because of the Bragg peak, tissues surrounding a tumor receive a reduced dose. ***Image source: Private from George Laramore***

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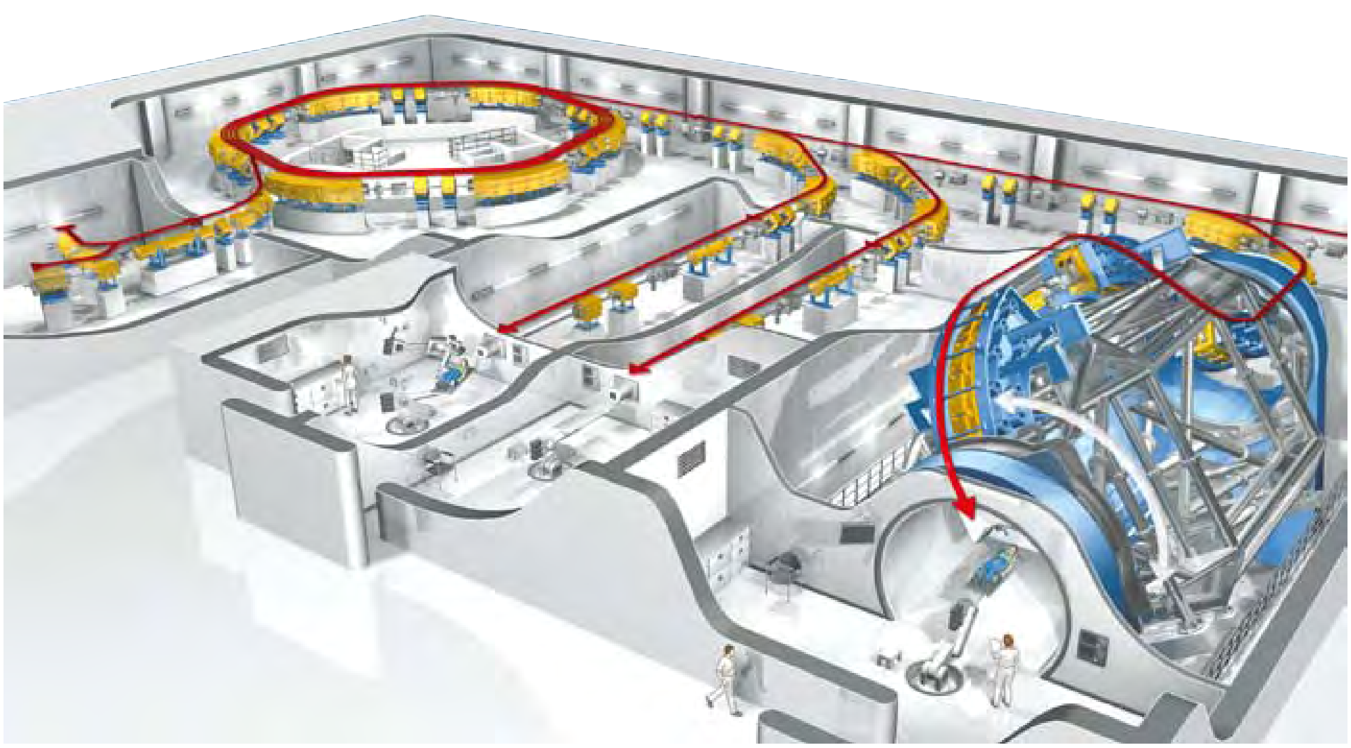
A cause for concern is the lack of clinical facilities offering treatment with carbon and other light ions.

skull base (95 percent at 15 years); squamous cell carcinoma of head and neck (94 percent at five years); and primary liver cancer (88 percent at five years). Carbon-ion therapy results include chordoma of skull base (91 percent at five years), stage T1-2 non-small-cell lung cancer (95 percent at five years) and early stage prostate cancer (92 percent at five years). In all these cases, patients received lower doses to large volumes of their normal tissues than they would have received with intensity modulated x-ray therapy, and as a consequence are judged to have a significantly lower risk of serious late effects.

NEEDS, OPPORTUNITIES AND TECHNOLOGIES

Currently, there are only eight clinical centers delivering proton beams in the U.S. The rest of the world has 22 operating centers, mostly in Asia and Europe. Demand continues to increase for proton therapy centers in the U.S. Patient waiting lists are long, and will continue to grow. Worldwide, 14 proton centers are under construction or in the active planning stage, of which three are in the U.S.

A cause for concern is the lack of clinical facilities in the U.S. offering treatment with carbon and other light ions, placing the nation at a growing disadvantage in this rapidly expanding field. After the shutdown of Berkeley Lab's Bevalac in 1991, two carbon-beam facilities, HIMAC in Japan and GSI in Germany, developed advanced facilities capable of treatment with light-ion beams. In Japan today, two are currently operating, a third is coming on line shortly, and a fourth begins construction soon. Heidelberg, Germany now has the first clinical center with multiple-ion capabilities from protons to carbon, including the first gantry for carbon beams; and two more are currently under construction in Germany. An Italian facility will begin treatments this year, and elsewhere in Europe two new centers are under construction, one each in France and Austria.



The Heidelberg Ion Therapy Facility has ion capability from protons to carbon. It includes two fixed-beam rooms and one rotating gantry suitable for carbon beams. ***Image courtesy of T. Haberer, Heidelberg Ion Therapy facility***

The U.S. is currently pursuing no projects for beams heavier than protons. There are compelling reasons to investigate the potential gain from high energy transfer characteristics (LET) of carbon ion beams to tissue and the gain from the superior dose distribution from the narrower penumbra of carbon beams. The nation clearly needs at least one facility with multiple-ion capabilities to make possible research in both clinical trials for different tumor sites and further development of beam-delivery technology. The barriers to development are the high cost of such a facility and identification of funding sources.

Another concern is the European and Japanese domination of the commercial sector, now providing integrated proton and light-ion facilities. In the U.S., industry has not yet entered this field.

Now is a propitious time to take stock: to assess the status of developments, to evaluate the role that the U.S. should have in this area of radiation treatment of cancer patients, and to develop a roadmap to achieve that goal. Continued optimization of the delivery of radiation will remain an important priority in oncology for the foreseeable future.

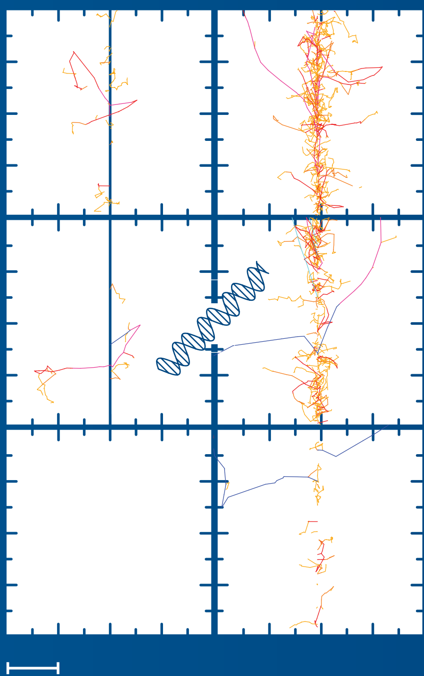
Clinical, medical physics and radiobiology

Despite the exceptional results achieved so far in particle beam therapy, there is substantial room for improvement. Many currently operating facilities use beam-delivery and field-shaping systems that can be significantly improved. Spreading the beam using "passive scattering" introduces material into the beam that degrades the sharp edges of the radiation field. Covering the maximum thickness of the treatment volume without changing the field size at each depth introduces more normal tissue into the full-dose volume. Passive scattering also requires higher initial beam intensity from the accelerator, adding to radioactive contamination of facility components, since large fractions of the beam scatter away from the usable beam direction.

Beam scanning, in which finely controlled, very fast magnets deflect a small-diameter beam across the radiation field is considered the method of choice for moving forward. However, patient safety concerns, reliability of controls and stability of accelerator and beam-delivery components mandate thorough testing and validation. An important problem is the requirement for highly accurate correction for motion and changes in the three-dimensional contour of the tumor during respiration and hence during irradiation of each field. Nonetheless, this technology is making steady progress. The multiple-ion facility in Heidelberg uses a system previously developed, successfully tested and used routinely for nearly a decade for clinical treatment at the GSI national laboratory in Darmstadt. Besides two-dimensional beam scanning by fast magnets, the carbon synchrotron provides pulse-to-pulse depth scanning by energy variation, allowing three-dimensional "volume painting" of any tumor, however irregularly shaped. A newly developed scanning system is beginning to see clinical use at MD Anderson Cancer Center in Houston. The major provider of today's installed proton facilities has also been working on a scanning system, which is in clinical testing at Massachusetts General Hospital. Implementation of beam scanning will need to become widespread to take maximum advantage of the superior physical properties of protons and ions.

Precision in defining and localizing the treatment volume is of great importance. Modern diagnostic tools—CT, MRI, PET—provide very high quality information, and clinicians have recently achieved much success in combining this imaging information with treatment-planning software to provide effective radiation-dose coverage of the identified target volume.

Ensuring that the beam-delivery system "knows" the actual location, size and depth of the target with an error of only a few millimeters remains of utmost importance. The ability to locate the position of the target volume in real



A simulation of microscopic energy transfer for fast-moving ion beams in tissue, protons on the left, carbon on the right. For comparison, a DNA molecule is shown to scale in the center. ***Image courtesy of M. Kraemer, GSI Helmholtz Center***

time and to have the beam track position changes to deliver the prescribed dose regardless of the target volume position is technologically feasible but requires substantial technical development.

Real-time imaging instrumentation using the beam itself through on-line biplanar imaging of fiducial markers or defined anatomic points, transmission tomography, and positron activation are promising approaches. Although demonstrations have taken place, these techniques are still in their infancy. Researchers have made tests of tracking a moving target volume in a phantom with a scanned beam at GSI, but this technique still requires significant development before it is ready for clinical application with real patients. Coordinating beam-on times with the phase of a patient's breathing cycle is also used for lung and liver treatments with proton and carbon ions in many centers. Such treatments lead to a commensurate extension in treatment times but do provide for an advance in motion compensation.

Understanding the response of healthy and tumor tissue to the higher LET of ions heavier than protons is of critical importance. As the LET for ions such as carbon varies significantly from entrance (high energy) to stopping point, the biological response to a carbon beam is complex. While researchers have accrued extensive radiobiology data with a variety of ions from protons to much heavier ions, much work remains. One dimension not yet fully explored is the use of several different ions, each with its own LET spectrum and biological effect, in combination in a single treatment. Also not fully explored is the effectiveness of combined chemotherapy and radiosensitizers with particle beam radiation therapy.

The key to further progress is R&D. The ideal and most efficient platform for conducting these studies would be a fully operational accelerator-based medical research facility capable of producing the full range of ion beams from protons to carbon, oxygen or even neon. Such a facility would enable biological studies; development of imaging technologies; exploration of scanning and controls for safe, flexible beam delivery; investigation of small-mass dosimetry instrumentation; and, perhaps most important, hosting of clinical research, clinical trials, and advanced patient protocols for newly developed technologies.

The key to further progress is R&D. The ideal and most efficient platform for conducting these studies would be a fully operational accelerator-based medical research facility.

Concept for a compact proton therapy system for treating cancer patients, based on a dielectric wall accelerator *Image courtesy of S. Hawkins, Lawrence Livermore National Laboratory*

The lack of federal support to at least partially cover the high capital costs of light-ion facilities has meant that progress in this important area is taking place exclusively overseas, with no current projects on U.S. soil. The most effective solution would be a facility built as a public or cost-shared public-private partnership. It would allow for revenue-generating patient treatments to reimburse the capital and operating expenses, but also allow for grant-funded research in physics, biology and clinical treatment.

Ideally such a facility should be associated with, and close to, a major medical academic center with a strong research-oriented radiation oncology program, and a university or laboratory with strong engineering and accelerator-physics resources. Such a facility is of paramount importance in order for the U.S. to participate fully in the long-term development of the next generation of medical-accelerator technology.

Current government policy is not oriented to address this goal. Since construction of the facility at Loma Linda University, DOE has not built facilities for human health care; the National Institutes of Health fund research, but rarely provide funds to construct cancer therapy equipment. The field of ion-beam therapy is blossoming in Europe and Asia, and for the U.S. to resume leadership requires a major policy change.

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TECHNOLOGY CHALLENGES

Accelerator technology has made great strides in expanding the availability of charged particles for clinical use. The key step has been the building of treatment facilities close to hospital settings, bringing the beams to the patients rather than transporting patients to the often stark and intimidating environments of accelerator facilities for research.

Commercial vendors have built and installed most of the current hospital-based proton-therapy systems. These vendors now offer integrated systems with state-of-the-art technology, either developed within industry or adapted from systems developed at universities or laboratories. For example, industry developed the gantry, which delivers the beam by rotating the delivery nozzle around the patient. In a complementary fashion, academic and laboratory scientists developed beam-shaping systems and dosimetry instrumentation.

All new commercially provided systems must meet clinical specifications for beam parameters, reliability and safety, and effective patient throughput. Achieving these specifications has led to large building complexes with massive concrete-enclosed vaults and huge gantries for beam delivery, all at very high costs. These costs are the prime deterrent to timely deployment of proton and light-ion therapy in the United States. The overriding consideration for the next generation of particle-therapy facilities is to reduce the size and costs, without sacrificing—in fact improving on—performance and reliability. There is a need for coordination of radiation and operational safety standards between the clinical and accelerator communities. Developing and implementing improved safety standards also requires strengthened interagency cooperation.

Improvements to the accelerator system, as well as to beam transport, instrumentation and gantry systems are important for accurate and flexible real-time dose delivery to the target tissues. Important areas for improvement are the speed and precision of beam control. Examples of specific parameters are beam position, energy, current and spot size on target.

Virtually all imaging procedures with CT, MRI and PET take place on supine patients. It is crucial to administer radiation and procure tumor images with the patient in the same position. Current standard procedures place the target tissue at the center of a vertical plane and rotate the beam around this "isocenter." X-ray systems are now compact enough to incorporate the accelerator and beam transport within the rotating gantry. But today's proton or ion beam gantries are very large (~13 meters in diameter) and very heavy. Reducing the size and cost of gantries or developing an alternate delivery strategy that maintains the necessary accuracy requires significant R&D.

The accuracy and response time of current dosimetry and beam-position monitoring devices also needs improvement, as the current instrumentation severely limits dose delivery and dose rate. Validation of patient prescriptions is currently very time-consuming, requiring many hours of overnight checks, adding to operating costs and possibly limiting patient throughput. Better instrumentation would streamline this process. Another goal is to develop non-intercepting instruments to minimize the deterioration of beam properties due to passage through detectors and transmission monitors on the way to the patient.

One opportunity ripe for development is the use of the beam itself, in low doses, to perform real-time three-dimensional imaging of the volume actually treated. Real-time PET imaging with radioactive beams, or with higher beam energies (particles must penetrate the body), and large-area, high-efficiency detectors could do such tomographic imaging, adding substantially to treatment accuracy and quality.

Advances in reliability through failure-mode analysis and other techniques can substantially improve system performance. Work on this topic is going forward throughout the accelerator world, particularly in the larger DOE facilities, and medical treatment systems could effectively apply the techniques as they develop.

Meeting the medium- and long-term goals of next-generation clinical requirements requires directed accelerator and beam-delivery R&D. A clinical research facility is the best means to accomplish the extensive testing and research required.

The number of particle therapy facilities worldwide is growing rapidly. In 2008, there were 70,000 patients at centers around the world, nearly double the number in 2005. ***Image source: J. Debus, Heidelberg Ion Therapy Center***

Reduction of the cost and size of proton and heavier-ion delivery systems requires expanding horizons beyond today's demonstrated technologies. New accelerating structures using superconducting cyclotrons, novel optics (fixed-field alternating-gradient-based designs) or ultra-high-gradient linacs could shrink accelerating and delivery systems to fit inside a compact treatment room. Researchers are studying and developing these concepts, but they will require extensive testing to prove readiness for clinical application. Lasers hold promise for generating proton beams, but formidable R&D challenges lie ahead before this technique would be demonstrated as ready for clinical use.

In summary, proton and heavier ion beams offer realistic potential for great advances in radiation therapy, but achieving these gains will require support from all sectors. The greatest challenge will be to find the paradigm for cooperation among all stakeholders; including federal agencies and the private sector.

It is critical to find a mechanism to develop a clinical research facility in the United States with the capability of producing ions from protons through carbon or oxygen.

FINDINGS

There is an opportunity to develop alternative sources for medical isotopes traditionally produced in reactors. Accelerator-based technology offers a ready solution for the production of ^{99}Mo as well as many other such isotopes.

Accelerators with particle energies from 10 MeV to several hundreds of MeV, operating year round, could meet the nation's needs for clinical and research isotope production.

Managing multiple high-intensity beams with the flexibility required of a dedicated isotope-producing facility requires basic accelerator, beam-transport, and targetry R&D.

For beam therapy, maximizing therapeutic efficiency and reducing as much as possible the dose delivered outside the treatment volume will require further improvements in beam-shaping and delivery designs for protons and heavier ions. Such optimization of beam quality and reduction of normal tissue exposure will contribute significantly to improved treatment outcomes.

Fully optimizing radiation treatments requires real-time imaging and motion tracking of target volumes, coupled with rapidly responding beam-delivery systems.

The overriding consideration for the next generation of particle-therapy facilities will be the reduction in the size and costs of the systems, while improving on current performance and reliability standards.

New accelerator, transport and delivery system technologies offer transformative opportunities for proton and ion-beam therapy. They should receive encouragement and support.

It is critical to find a mechanism for government funding or for effective public-private partnerships for the development of a clinical research facility in the United States with the capability of delivering ion beams from protons through carbon or oxygen. The facility would serve as major research resource, a test site for clinical trials and for radiobiological and medical physics to explore the unique potential of proton and heavier ion beams to treat cancer patients.

Accelerators for Industry

Today in the United States many thousands of particle accelerators are at work across an extraordinary spectrum of fields from basic research to industry. Around the world, industry both designs and manufactures accelerators for research and industrial uses and uses accelerators for a multitude of applications. Innovations in accelerator technology beget new applications and vice versa, each reinforcing the other and building the potential for future industrial and scientific uses for accelerators.

Worldwide, hundreds of industrial processes use electron-beam and ion-beam accelerators. Electron-beam applications center on the modification of material properties. They provide technology for the cross-linking of polymers, for surface treatment, and for pathogen destruction in medical sterilization and food irradiation. Ion-beam accelerators, which accelerate heavier particles, find extensive use in the semiconductor industry in chip manufacturing and in hardening the surfaces of materials such as those used in artificial joints. Industry is also pursuing the manufacture and application of superconducting radio-frequency, or SRF, accelerators. These SRF accelerators presently find use mainly in basic research and defense applications.

Private-sector organizations are the principal developers of industrial electron-beam and ion-beam accelerators and of their many successful industrial applications in markets that have evolved over decades. Government-funded national laboratories are the major developers and main users of SRF accelerators, with private-sector involvement in supplying SRF cavities, klystrons, couplers and cryogenic components.

Crosslinking of polymers by an electron beam, as in this Illinois plant, improves heat resistance of coatings for wire and cable.
Photo: Reidar Hahn, Fermilab

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Around the world, industry both designs and manufactures accelerators for research and industrial uses and uses accelerators for a multitude of applications.

A Rhodotron, a commercial electron-beam accelerator for industrial applications including sterilization of medical devices
Image courtesy of IBA

To take advantage of the significant potential to increase existing markets and to develop new accelerator applications for all three technologies, both industry and government will need to address critical barriers to expansion. Electron-beam accelerators, for example, could replace thermal processes in the curing of inks and coatings, with energy savings and benefit to the environment. However, concerns about reliability and financing make customers wary of changing to a new accelerator process from a familiar thermal one. Similar concerns block the development of applications for waste water and flue-gas treatment. A cost-sharing government-industry partnership for long-term demonstrations would reduce risk and open up potential markets for accelerator technology.

Several national-laboratory programs have SRF accelerator components in the procurement pipeline, but U.S. industry currently lacks the capacity to produce the required quantities on the estimated schedules. As the only major U.S. customer for SRF technology for the next five years, the government must integrate industry into SRF programs, as Japan and Europe have done, in order to prepare U.S. industry for the cost-effective manufacture of key SRF accelerator components to meet government procurement schedules. Without a major government-supported industrialization effort, most of these procurements will go offshore.

Two factors retard the growth of accelerator technologies for industry. First, there is a need for more Department of Energy engagement in technology exchanges within existing organizations, and for workshops and other regular interactions with industry. Small companies often lack R&D resources and need ways to address their R&D needs while protecting intellectual property. Second, high risk makes customers hesitant to switch from existing processes to particle accelerator-based technologies. Government support for user facilities and demonstrations could go far to establish the value of accelerators in saving energy and preserving the environment.

Industrial applications of accelerator technology comprise the areas of electron-beam, ion-beam and SRF technology. Other applications of accelerated electrons, not discussed in this section, include scanning electron microscopy, electron-beam welding, and medical diagnosis and treatment.

Electron beams

There are approximately 1700 high-current, industrial electron-beam accelerators producing tens of billions of dollars of value-added products in diverse market areas worldwide.

The largest industrial use of electron-beam accelerators is for the modification of polymers by cross-linking, the formation of three-dimensional chemical links between adjacent polymer segments. Cross-linking renders materials insoluble in solvents that would dissolve non-cross-linked materials. Surface curing with low-energy electron beams (70 to 300 keV) is the fastest-growing market segment because of the improved energy efficiency of these high-speed processes and their environmentally friendly elimination of volatile organic solvents from the manufacturing process. Uses include cross-linking of the polymers for insulation on electrical wires and for heat-shrinkable tubing for protecting wire and cable connections, making these products more flame retardant for automotive under-hood wiring and other applications.

Cross-linking of heat-shrinkable films, most widely used in food packaging, makes up a large share of the electron-beam market. Such films extend the shelf life of meat, produce, poultry and dairy products and provide tamper-resistant packaging. The major producer of cross-linked packaging uses more than 125 industrial electron-beam accelerators in its global manufacturing operations.

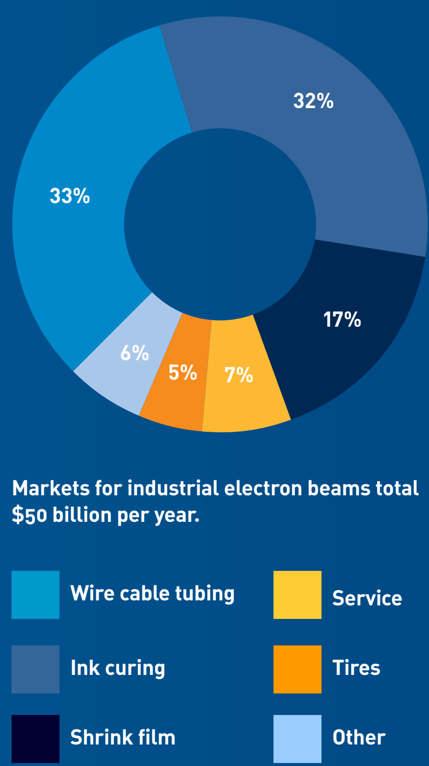
Cross-linked closed-cell polyethylene foam cushions the interior of automobile roof liners and door panels. The tire industry uses electron-beam processing to partially cure the rubber stock to stabilize tire cord placement and to produce better-balanced tires. The manufacture of heat tracing systems and polymeric switches uses cross-linked conductive polymers.

Electron-beam curing of inks, coatings and adhesives eliminates the use of volatile organic compounds, enabling manufacturers to attain high production speeds with minimal energy consumption and reduced environmental impact. In these applications, "green" electron-beam technology yields as much as a 90 percent reduction in power consumption compared to conventional thermal drying and curing.

The manufacture of hydrogels for wound and burn treatment employs electron-beam technology. High-energy electron beams and x-rays derived from electron-beam systems sterilize medical equipment. Ionizing radiation eliminates food-borne pathogens, such as *E. coli*, *Salmonella* and *Listeria*, from meats, poultry and other food products, and disinfects grains and spices. A small number of service centers around the world use electron beams for food irradiation. Widespread public mistrust of food irradiation constitutes a significant barrier to expansion. However, the cumulative cost to Americans of foodborne illnesses is $152 billion annually, according to a 2010 Georgetown University study. The Centers for Disease Control and Prevention estimate that there are 76 million cases of food-related illness in the U.S. each year, resulting in 5000 deaths and 325,000 hospitalizations. Increased emphasis on food safety and growing concerns over the safety and supply of the radioactive isotope ^{60}Co, are likely to stimulate demand for food irradiation using electron beams and x-rays derived from high-energy, high-power electron-beam accelerators.

Other industrial uses for electron-beam technology include degradation of polytetrafluoroethylene, or Teflon®, for manufacturing micronized lubricants; grafting of filter membranes and battery separators; and enhancement of polyethylene water pipes. The use of electron beams to treat seeds and soil shows promise for increasing crop yields.

Electron-beam curing of inks, coating and adhesives eliminates the use of volatile organic compounds, enabling manufacturers to attain high production speeds with minimal energy consumption and reduced environmental impact.



Markets for industrial electron beams total $50 billion per year.

Image source: IAEA Working Material on Industrial Electron Beam Processing

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Converting metal-coating facilities to electron-beam technology could realize a 95 percent savings in power demand.

NEEDS, OPPORTUNITIES AND TECHNOLOGIES

Energy, the environment and electron beams

Industrial electron-beam processing has the potential to conserve energy in industrial processes, to remediate stack gas emissions from fossil-fueled power plants, to purify drinking water, and to disinfect and detoxify municipal and industrial waste water. The Energy and Environment chapter of this report discusses these applications in more detail.

Metal coatings

While it can be difficult to quantify the cumulative environmental impact of low-energy electron-beam processes such as the curing of printing inks, coatings, adhesives and laminations, it is easier to calculate the effects for a narrower market segment, the metal coating industry. Based on U.S. Environmental Protection Agency projections, the U.S. has about 80 facilities that apply coatings to steel or aluminum to make approximately 1.8 trillion square meters of precoated metals for fabricating rain gutters, appliance housings, metal doors, and outdoor panels for metal buildings. These facilities currently use thermal processes consuming approximately 166 megawatts of power just to dry the coatings. Converting these facilities to electron-beam technology could realize a 95 percent savings in total power demand. Electron-beam curing would also enable these facilities to comply with the U.S. EPA directives to attain the Maximum Achievable Control Technology, or MACT, for reduction of emissions of volatile organic compounds.

Coated cables at Electron Beam Technologies, Inc. in Kankakee, Illinois
Photos: Reidar Hahn, Fermilab

Electron beams and acid rain

Currently, coal-fired generating plants meet nearly half the total annual U.S. electric power demand of about 4000 terawatt-hours. Appropriately sized electron-beam accelerators at larger plants could significantly reduce the acid-rain-forming emissions they produce. Small-scale experiments in Japan and a full-scale demonstration plant in Poland have shown that electron-beam treatment of nitrogen and sulfur oxides eliminates about 90 percent of both these emissions. Other technologies, such as the use of scrubbers, cannot cost-effectively eliminate nitrogen oxides. Injection of ammonia into flue gas before electron-beam treatment causes the ammonia to react with these gaseous wastes and converts them into saleable fertilizer. Supported by the International Atomic Energy Agency in the mid-1990s, the full-scale Polish electron-beam flue-gas treatment facility cost approximately $25 million.

The typical electron-beam power requirement is one percent of the electric power output of the plant. Meeting the entire U.S. need would require about 2500 megawatts of electron beam power. Even with a beam power of 500 kilowatts for each accelerator, this would generate a demand for some 5000 accelerators using current technology. Adopting electron-beam technology in the U.S. would require building and operating a full-scale facility to demonstrate feasibility and cost effectiveness to power companies.

Water treatment

Electron-beam treatment can disinfect and decontaminate both waste water and drinking water. Projects in Boston and in Miami-Dade County, Florida, funded by the National Science Foundation, have shown the feasibility of disinfecting municipal waste water with relatively low doses of electron-beam treatment. Further NSF project studies at the Miami-Dade facility have shown that electron-beam treatment can break down water-borne organic toxins such as halogenated hydrocarbons. An existing full-scale facility in Korea uses electron beams from an accelerator provided by Russia's Budker Institute to break down residual dyes from a fabric plant before discharge into a river.

Shrink Wrap

An electron zap turns flimsy plastic into sturdy shrink wrap

If you buy a Butterball turkey this Thanksgiving, you have particle accelerators to thank for its freshness. For decades now the food industry has used particle accelerators to produce the sturdy, heat-shrinkable film that Butterballs come wrapped in.

"Particle accelerators tie the molecules of plastic together and make the film tougher mechanically. It doesn't crack or tear," says Marshall Cleland, a technical advisor at IBA Industrial, an international company that has been manufacturing particle accelerators for commercial use since 1988.

Understanding how accelerators give crosslinked shrink film its unique properties requires a refresher course in chemistry.

Heat-shrinkable film—commonly known as shrink wrap—is made of polyethylene plastic. The plastic molecules, called polymers, are long chains of carbon atoms strung together like pearls. Each carbon atom also connects with two hydrogen atoms, leaving it no room to bond with anything else.

"The fully saturated carbon had its full meal, including dessert, and becomes chemically inert," Cleland says. "If you heat it to the boiling point of water, it will turn into a syrupy mess."

However, when hit with a beam of electrons from a particle accelerator, the plastic's polymer strings become chemically active.

The electron beam knocks hydrogen atoms off the polymer chains, leaving the polymers hungry to fill those vacancies. If conditions are right, the carbon atoms in one chain bond with carbons in neighboring chains—and those carbon-carbon bonds are incredibly strong.

"The whole thing starts to knit together. Instead of being loose threads, it is sort of like a fishnet where everything is tied together," Cleland says. "It is what we call a cross-linking reaction."

When fully cross-linked, the plastic "becomes elastic if you heat it to boiling temperature, but it won't melt," Cleland says. After electron-beam treatment, the plastic is stronger and more heat resistant. It can be heated and stretched into a thin film without ripping. When cooled to room temperature, the cross-linked plastic retains its expanded shape. Place something inside it, such as a Butterball turkey, and apply heat, and the plastic shrinks back down to its original size, resulting in an air-tight wrapping.

The food industry purchases these cross-linked products from plastic manufacturers in large rolls or bags, depending on how the film will be used. You will find cross-linked shrink film wrapped around many items in the grocery store, such as turkeys, produce, and baked goods, as well as around board games, video games, DVDs, and CDs. "It's a big business," Cleland says.


Photo: Reidar Hahn, Fermilab

Electron-beam treatment of municipal water supplies can reduce or eliminate the need for chlorine and other chemicals that cause interior corrosion in water pipes and that create toxic halogenated organic compounds. Electron beams can break down pharmaceutical by-products passed by humans into sewage systems. Such molecules are often too small to be captured by membrane filtration processes. Based on a U.S. per capita consumption of 300 gallons of water per day, treating half the water in US municipal systems with electron beams would represent a market for 500 accelerators at 500 kilowatts each, using current technology. Acceptance by municipal water systems would require a full-scale, full-time operational electron-beam facility to demonstrate its long-term feasibility, safety and cost-effectiveness.

EMERGING OPPORTUNITIES

Electron beams for producing biofuel

Electron beams offer an alternative to the use of edible food crops, mostly corn, for the production of ethanol to reduce gasoline consumption. Electron beams can break down nonedible starch and cellulose to make these renewable resources usable as ethanol-producing fermentation stocks. In contrast to conventional methods of chemical breakdown of renewable resources, which generate toxins that interfere with fermentation, pretreatment of cellulose and starches with electron beams permits enzymatic conversion of these nonedible materials to alcohol without diverting corn from the food supply. In 2008, the U.S. consumed 522 billion liters of motor vehicle fuel. Replacing 10 percent of that fuel with alcohol derived from cellulose or starch would require approximately 650 500-kilowatt electron-beam accelerators.

Applications of electron-beam technology include cross-linking of polymers in radial tires, making tire manufacture less expensive and more environmentally friendly. *Image courtesy of Analytical Research LLC*

Wood-polymer composites

Electron-beam- and x-ray-cured materials impregnated into or applied on wood make it stronger and more resistant to damage from moisture, mold and fungi. Such accelerator-based processes use less energy and generate far fewer volatile organic compounds than conventional chemical wood-preservation processes.

X-ray-cured carbon fiber composites

Replacing steel with carbon fiber composites in cars, including the chassis, would reduce the weight of the body by about 80 percent. Such weight savings could lead to a 50 percent reduction in vehicle fuel consumption—an effective way to double gas mileage. Electron beams and x-ray curing can spur the use of carbon fiber composites in the automotive industry. X-ray curing can take place in the mold and in relatively short exposure times.

THE TECHNOLOGY OF ELECTRON BEAMS

Industrial users characterize electron accelerators by the energy of the electrons they produce, the beam current, and the acceleration technique. The electron energy determines the depth of penetration into a target material; the beam current determines the material processing rate. Low-energy accelerators range from 70 keV to 300 keV. They are self-shielded and require no further radiation shielding when operated in uncontrolled areas. Medium-energy accelerators range from 300 keV to 5 MeV. High-energy industrial electron-beam accelerators produce electrons from 5 MeV to 10 MeV.

Different energy regimes require different technologies. Low-energy electron-beam accelerators use direct-current power supplies and can produce wide (up to three-meter) beams with the accelerating potential between the electron source and the beam window foil. These are the accelerators typically used for curing inks, coatings and adhesives; cross-linking polymers in thin plastic films; surface sterilization of medical devices and food packaging; and cleaning up polluted liquids and gases. The preeminent manufacturer of pressure-sensitive adhesive tapes, which uses low-energy electron-beam processing, has pointed to the need for reliable, down-sized lower-energy accelerators, and U.S. manufacturers in this area have responded.

The U.S. industrial developers of low-energy electron-beam equipment have collaborated with others to provide modest-cost pilot-scale facilities for processing flexible substrates, such as paper and films, and for integrating this pollution-free and energy-efficient technology into existing industrial processes, such as printing and coating operations.

Medium-energy electron-beam accelerators use multistage direct-current power supplies and multiple-gap acceleration tubes. They can produce beams up to three meters wide. Medium-energy electron beams find their most common uses in cross-linking polymers for wire and cable insulation, heat-shrinkable plastic tubing and films, molded plastic parts and closed-cell foams; and in the partial cross-linking of rubber components in tires. They also sterilize medical devices, but until now less frequently than do radioactive isotopes. The treatment of flue gases and municipal and industrial waste water is an important future application for medium-energy accelerators.

The highest-energy industrial electron-beam accelerators, at most 10 MeV, are not direct-current devices, but are either microwave linear accelerators or radio-frequency devices. Industrial users do not use accelerators above 10 MeV, so as to avoid inducing radioactivity in treated materials. The most common industrial application for high-energy accelerators is in the bulk sterilization of prepackaged medical devices and in cross-linking of thicker plastic products including piping and molded parts.

The two types of x-ray generators include broad-spectrum and laser-like units. Broad-spectrum units use high-energy electron accelerators to produce x-rays by stopping the electrons in a heavy-metal target. While electron-beam processing has a higher through-put, x-rays can treat or sterilize materials too thick or too dense for direct treatment with electrons. Whereas 10 MeV electrons can treat materials from two sides up to about 8 cm, the optimum thickness for x-ray treatment from opposite sides is about 30 cm. X-rays from electron-beam accelerators also offer a practical and safe alternative to gamma rays from radioactive isotopes. Electron synchrotrons and free electron lasers, which produce low-energy, but high-quality x-rays, are most frequently used in imaging and research applications and are not suitable for the industrial processing of materials.

Industrial accelerators energy range table

	Low energy	Medium energy	High energy
Energy range	**70 keV–300 keV**	**300 keV–5 MeV**	**5 MeV–10 MeV**
Features	**Wide unscanned beams less ≤3 m**	**Scanned beams ≤3 m**	**Linacs or SRF**
Current applications	**• Curing of inks • Crosslinking of polymers • Surface sterilization • Remediation of liquids and gases**	**• Crosslinking of wire and cable insulation • Crosslink heat-shrinkable plastic tubing • Manufacture of closed-cell foam • Crosslink plastic • Crosslink rubber • Medical sterilization**	**• Bulk sterilization of medical devices • Crosslinking thicker plastics**

Electron beams offer an alternative to the use of edible food crops for the production of ethanol to reduce gasoline consumption.

Most of the cereal boxes in the grocery store aisle are printed using electron-beam-cured inks and coatings. Printing with this technology allows the boxes to run through web press technology faster because of the faster dry time. ***Photo: Reidar Hahn, Fermilab***

Ion beams

Ion-beam accelerators are essential to the manufacture of computer chips for the multibillion-dollar global semiconductor industry. Currently, about 10,000 ion-beam accelerators are in use worldwide to "dope" the silicon or germanium base to create electronic circuitry for computer chips. Ion implantation can modify material properties, another tool for the semiconductor industry. This can transform the near-surface region of the base material into a fully or partially amorphous state, providing a method for cofabricating strained and relaxed crystalline, polycrystalline, or amorphous structures during integrated device fabrication.

In contrast to electron-beam processing, ion-beam implantation accelerates particles, such as boron, phosphorus or arsenic ions, of much higher mass than electrons. The accelerating energy is usually less than 500 keV, and penetration in silicon is in the micron range. In 2008 about 500 ion implanters were sold. Because all digital electronics depend on ion implanters, they have a profound economic impact, and their use extends far beyond the semiconductor industry. Besides their role in complementary metal-oxide semiconductor, or CMOS, fabrication and the separation by implanted oxygen, or SIMOX, fabrication processes, ion implanters have many other industrial applications, such as cleaving silicon; micro-electro-mechanical-systems, or MEMS, fabrication; hardening of the surfaces of metals and ceramics for high-speed cutting tools and artificial human joints; and modification of the optical properties of materials.

Beyond semiconductor manufacture, the main functional areas with interest in ion implantation are catalysis, solar energy and optical materials development, along with fundamental science investigations associated with radiation effects in materials proposed for nuclear-waste stabilization and the next generation of materials for nuclear reactors, discussed further in the chapter on Energy and Environment.

Ion beams are widely used in nondestructive elemental analysis, by simple scattering of ion-beam particles from MeV accelerators, by inducing nuclear reactions, or by using particle-induced x-ray and gamma-ray analysis. Researchers use these methods to analyze materials in a variety of fields, including semiconductor research, environmental monitoring, geological and oceanographic studies, biomedical science and even art authentication. Ion-beam accelerators are also configured to be the most sensitive mass spectrometers for measuring trace radioisotope concentrations, including precise measurement of the ^{14}C to ^{12}C ratio for dating artifacts. This capability is an essential tool in geology, archaeology, drug discovery and climate studies, and could play a role in climate treaty verification. For more than 25 years, MeV ion accelerators have contributed to the fundamental understanding of such highly technical areas as high-density memory devices, silicon-based light amplifiers for fiber-optic communication, and the diagnosis of disease.

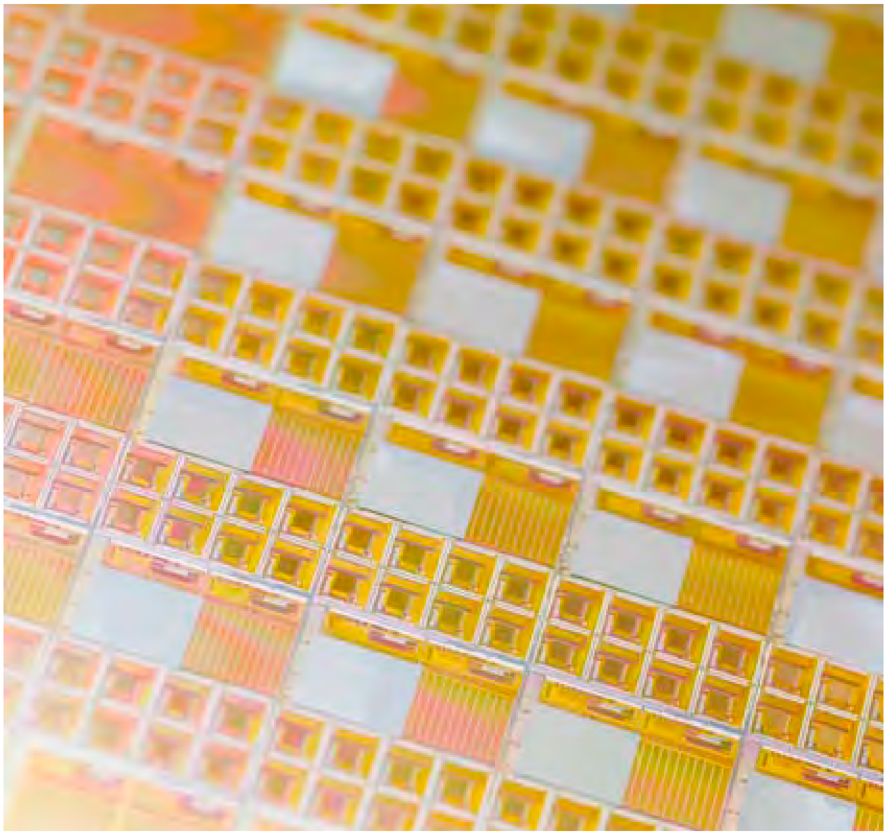
Ion implantation into artificial joints is critical for the success of joint replacements.
Image: Sandbox Studio

ION-BEAM TECHNOLOGY

The trend toward ever-smaller semiconductor components requires technology that delivers high beam currents to provide the requisite dose levels at low energies for shallow implantation. Reduced ion energies make it difficult to maintain convergence of the particle beam due to the mutual repulsion of ions bearing like charges. High-current ion beams have high concentrations of similarly charged ions that tend to diverge. One solution employs a ribbon-type ion beam, with a substantially greater cross-section than that of a traditional pencil-type beam. A typical pencil beam has a diameter of about 1-5 cm, whereas a ribbon-type beam may have a height of about 1-5 cm and a width of about 40 cm. A larger beam area results in smaller current density for a given beam current. Ribbon-type beams, however, present unique challenges that require a combined effort of basic beam-physics studies and targeted ion-source development to increase the delivered useful dose during implantation. Using other types of ion sources, especially types that do not rely on consumable electrodes, would enhance implantation productivity by reducing maintenance shutdowns.

The central role of ion-beam accelerators in nondestructive elemental analysis has led to widespread application of these technologies and to a demand for smaller size and lower cost. This demand, from both research institutes and industries, has fostered initial substantive success, for example in the accelerator mass spectrometry area where designers have successfully lowered accelerator voltages while maintaining sensitivity. An exemplary level of collaboration between research institutes and manufacturing industry has been the essential element in the initial rapid progress.

Ion beam accelerators are essential to the manufacture of computer chips for the multi-billion-dollar global semiconductor industry.



About 10,000 accelerators are in use worldwide to "dope" the silicon or germanium base to create electronic circuitry for computer chips. ***Photo: Reidar Hahn, Fermilab***

3

Industry is pursuing the manufacture and application of superconducting radio-frequency, or SRF, accelerators. The largest requirement is for particle accelerator research facilities to explore key areas of basic science.

Superconducting radio-frequency accelerators

SRF APPLICATIONS

The U.S. government will dominate demand in the domestic market for SRF technology over the next five years. The largest requirement is for particle accelerator research facilities to explore key areas of basic science. Government demand is also evolving for free electron laser systems for defense applications and large-scale cargo inspection facilities. Superconducting radio-frequency accelerators currently operate at the Spallation Neutron Source facility at DOE's Oak Ridge National Laboratory, the Continuous Electron Beam Accelerator Facility at DOE's Thomas Jefferson National Accelerator Facility and the Argonne Tandem Linac Accelerator Facility at Argonne National Laboratory. A European organization is currently procuring SRF accelerator technology for the X-ray Free Electron Laser facility, or XFEL, to be built in Hamburg, Germany. Several future programs in which the U.S. government might be involved, such as the proposed International Linear Collider, also incorporate SRF technology. The ILC would require 2000 cryomodules containing 18,000 SRF cavities procured from sources around the globe, at an estimated cost of over $3 billion. Besides these science programs, the U.S. Navy has adopted SRF technology for potential future shipboard defense systems.

SRF TECHNOLOGY

At the heart of an SRF accelerator is a hollow structure called a cavity, made of a superconducting material, such as niobium, chilled to near absolute zero with liquid helium. A microwave generator fills the cavity with a radio-frequency electric field. The electric field accelerates charged particles injected into a string of connected cavities. Superconducting cavities conduct electric current with extremely small loss of energy so that almost all the electrical energy goes into accelerating the beam, rather than into heating up the accelerating structures themselves. The design of SRF accelerators varies to fit an accelerator's energy requirements and particle types. Superconducting radio-frequency accelerators incorporate multiple cavities into linear assemblies known as cryomodules. Accelerator builders string multiple cryomodules together to increase the energy of the accelerated beam.

Estimated SRF accelerator industrial market to support U.S. science programs 2010-2015

Project	SRF Cavities	Cryo Modules	Est. Market (in millions)
Continuous Electron Beam Accelerator Facility (CEBAF) Upgrade, Thomas Jefferson Lab National Accelerator Facility, Newport News, VA	86	10	17
Facility for Rare Isotope Beams (FRIB), Michigan State University, East Lansing, MI	336	45	100
Proposed Project X, Fermilab, Batavia, IL	445	58	87
Proposed Cornell Energy Recovery LINAC, Cornell University, Ithaca, NY	304	58	57
Proposed SNS Upgrade, Oak Ridge National Laboratory (ORNL), Oak Ridge, TN	36	9	18
TOTAL	1207	160	279

EMERGING OPPORTUNITIES FOR VERY-HIGH-ENERGY ACCELERATORS

Synchrotron light sources

Synchrotron light sources, typically operated at government-owned facilities, provide photons from infrared to hard x-rays for multiple user communities. These light sources provide intense beams of coherent photons in small energy bands of less than an electron volt for research in physics, chemistry, materials science, medicine and biology. Industrial applications also use experimental techniques developed at light sources. The study of catalysts for the petrochemical industry, for example, in the production of fuel for combustion engines and for fuel cell technology, uses x-ray absorption spectroscopy.

Compact light sources

The growing needs of industrial accelerator applications and advancements in accelerator technology—in particular in the field of SRF and superconducting magnets—highlight the need to develop compact light sources and facilities specialized for industrial users as part of an industry-friendly program of accelerator development.

Neutron sources

Compact, electrically sourced neutron generators, currently available from several industrial suppliers offer an alternative to the use of radioactive isotopes in oil and gas field exploration. Improvements in the lifetime of the tube and intensity of the neutron emission would expand their commercial utility.

Nuclear energy

One way to use spent nuclear waste and to produce more nuclear power is to treat plentiful isotopes such as ^{232}Th and ^{238}U with fast neutrons from an intense proton accelerator (1 to 2 GeV beam energy, >10 megawatt beam power). Such an accelerator-driven subcritical system, or ADS, operates below criticality. Superconducting radio-frequency accelerator technologies make the construction of such proton accelerators feasible. Research and development are proceeding in Japan, China, Europe and India to make an ADS system a reality. Should the U.S. decide to give this technology national priority, the government must partner with U.S. industry in the construction of both the proton accelerator and its associated reactor. Each SRF linear accelerator, or linac, would contain approximately 150 superconducting cavities housed in 20 cryomodules. Such linacs must operate with extraordinary reliability, with very few interruptions per year. Designing and building the requisite safeguards for such stable operation requirements, far more stringent than for a research environment, will require industrial expertise. The chapter on Energy and Environment further discusses these applications.

Developing suppliers for emerging SRF applications

Approved and proposed U.S. science projects will require over 1200 SRF cavities of various types and with different frequencies, through 2015. The U.S. Navy and emerging areas will require additional cavities along with other high-tech components such as microwave couplers and klystrons. Although the technical capability exists, there is limited existing U.S. industrial capacity to produce these cavities and components. An aggressive industrialization program would establish a national capability to meet the needs of these government-funded projects. Without such a program, offshore industries will supply these components, as well as the design and construction of the accelerators themselves. The estimated demand for industry to supply accelerator components to government programs over the next five years approaches $300 million.

A multi-celled elliptical superconducting radio-frequency cavity ***Photo: Reidar Hahn, Fermilab***

3

Strengthened relationships between industry and the program offices of DOE, through workshops, organizations and other means, would encourage the development and use of accelerators to meet national needs.

Norman R. Augustine, retired chairman and CEO, Lockheed Martin Corporation, delivered the keynote address at the Accelerators for America's Future Symposium.
Photo: Reidar Hahn, Fermilab

INDUSTRY CHALLENGES

Lack and loss of knowledge and experience hamper development of accelerator technology and its end-use applications, especially in small market areas. Universities could address this growing problem by offering courses in the practical uses of industrial accelerator technologies to meet future national needs. In collaboration with the Food and Drug Administration and the Environmental Protection Administration, there is an opportunity for DOE to provide important assistance in educating the public and publicizing the economic and practical benefits of particle-beam processing, for example.

Strengthened relationships between industry and the program offices of DOE, through workshops, organizations and other means, would encourage the development and use of accelerators to meet national needs in many areas. Small company suppliers and users need continuing reliable sources of information about the portfolio of resources available through the Department of Energy: the Advanced Research Projects Agency-Energy, or ARPA-E, the Energy Frontier Research Centers, and the industrial and manufacturing support programs of the DOE offices of Energy Efficiency and Renewable Energy, Fossil Energy, and Nuclear Energy. Such programs directly support technology development through commercialization. Industry needs information on how to apply for time at DOE-supported user facilities and how to follow the protocols for applying for DOE support. Ensuring the funding of Phase 3, commercialization, of promising accelerator-based Small Business Innovation Research, or SBIR, grants will further encourage the industrialization of accelerator technology.

Access to existing light sources is critical for materials and biology research. Compact, high-brightness light sources for single users could increase the use of light sources at universities and in industrial research. Research and development of this technology merits DOE consideration.

Industrial intellectual property must be preserved and respected. With respect to their research results, national laboratories and publicly funded universities and their programs should focus on publishing results instead of patenting and licensing intellectual property. For example, in the U.S., accelerator users must pay royalties to a government agency to obtain simulation codes, many developed at U.S. national laboratories, for simulating radiation. In Europe, industrial users can obtain such codes free from CERN, the European Organization for Nuclear Research.

The application of electron-beam processing in coating technologies, sterilization, material modification and other processes can have a significant impact on energy and resource conservation. It would be helpful to have increased access to DOE user facilities to demonstrate electron-beam technology. Access to such facilities should be industry friendly. In other countries, including Japan, Brazil, the Russian Federation, Poland and Malaysia, government laboratories with high-current electron-beam accelerators serve the needs of the industrial processing community. DOE could also help to guide public policy related to incentives or subsidies to increase the use of industrial accelerators. In other countries, government policy proactively supports this energy-efficient, environmentally friendly industrial process technology.

The deployment of radioactive sources represents a national security risk. Growing concerns exist about the supply, security and transport of radioactive isotopes for use in areas such as industrial R&D, basic research, medical tracers and security applications. Electrically powered radiation sources offer alternatives to the use of radioactive nuclides such as ^{137}Cs and ^{60}Co. Sealed neutron accelerators would also provide an alternative to radioactive neutron sources such as ^{252}Cf.

New accelerators may require the industrialization of new technologies, such as SRF cavities, superconducting magnets and other accelerator components, such as very thin windows for low-energy electron beams. To date, the free-market economy in the U.S. has largely met the demand for industrial accelerators. Readying U.S. industry to meet the significant demand for SRF technologies for the government market over the next five years will require a formal industrialization program between government and industry. Without such a program, offshore suppliers will receive these taxpayer dollars. Federal funding might be most useful in supporting nonrecurring engineering expenses, in order to share the risks of developing critical components.

Electron-beam technology has proven effective in remediating industrial air pollution, ground contamination, and contamination of waste water and potable water. Large-scale facilities to evaluate the practical aspects of electron-beam processing in these environmental areas would augment existing or new utility installations. Besides the user facilities supported by the DOE Office of Science, the industrial and manufacturing development programs of the DOE Offices of Energy Efficiency and Renewable Energy, Fossil Energy, and Nuclear Energy might have an interest in such pilot facilities.

FINDINGS

In the United States today, a wide variety of industrial applications use particle accelerator technologies. In the U.S., for industrial applications, accelerator technology and market development have, for the most part, evolved through the free-market economy, which largely continues to satisfy the needs and requirements for new applications. However, federal resources could help to expand new and existing industrial applications.

Federal agencies could encourage the replacement of inefficient, environmentally harmful thermal processes with energy-efficient and green electron-beam or x-ray processes. Such a change would save energy and eliminate volatile organic compounds from the environment. It would reduce the U.S. dependence on foreign oil for electric power generation.

DOE could support national centers of expertise and university programs where investigations of electron- and ion-beam processing train future experts. Institutions with suitable capabilities should support fundamental research into the physical, chemical and biological effects of accelerated electrons and ions on materials at all energies. Supporting university research and education in the area of accelerator technology and its uses, especially those with high potential for economic and practical benefit, will also have value to industry.

Establishing large-scale industry-friendly user facilities would help to confirm the practical aspects of accelerator technologies for environmental applications to treat emissions from fossil-fuel-fired power plants; and to treat drinking water, municipal waste water and industrial effluents.

The public would benefit from education about the benefits of accelerator-based technologies. While medical applications have done much to allay widespread fear of radiation, misinformation and mistrust on the subject persist. Education about safety records and environmental benefits of large-scale "green" applications would help to overcome misperceptions and stimulate interest in the industrial use of accelerators.

Federal agencies could encourage the replacement of inefficient, environmentally harmful thermal processes with energy-efficient and green electron-beam or x-ray processes.

Image: Sandbox Studio

Adventures in Accelerator Mass Spectrometry

Oetzi, the 5000-year-old Neolithic man from the Alps, the "Great Conveyor Belt" of ocean circulation, the permeability of the blood-brain barrier to insecticides, the glaciers in high-mountain regions of temperate zones, and Paris's Louvre museum have something in common: particle accelerators.

Since the field began about 30 years ago, accelerator mass spectrometry, or AMS, has revolutionized areas as diverse as archeological dating, climate research and art authentication. Determining the exact ratio of a radioisotope to the stable isotope of the same element present in an artifact or other material allows researchers to determine its age and other critical properties. Accelerators have taken center stage in a spectrum of fields from geology to drug development by virtue of their ability to make extremely precise measurements of long-lived radioisotopes at ultra-low concentrations.

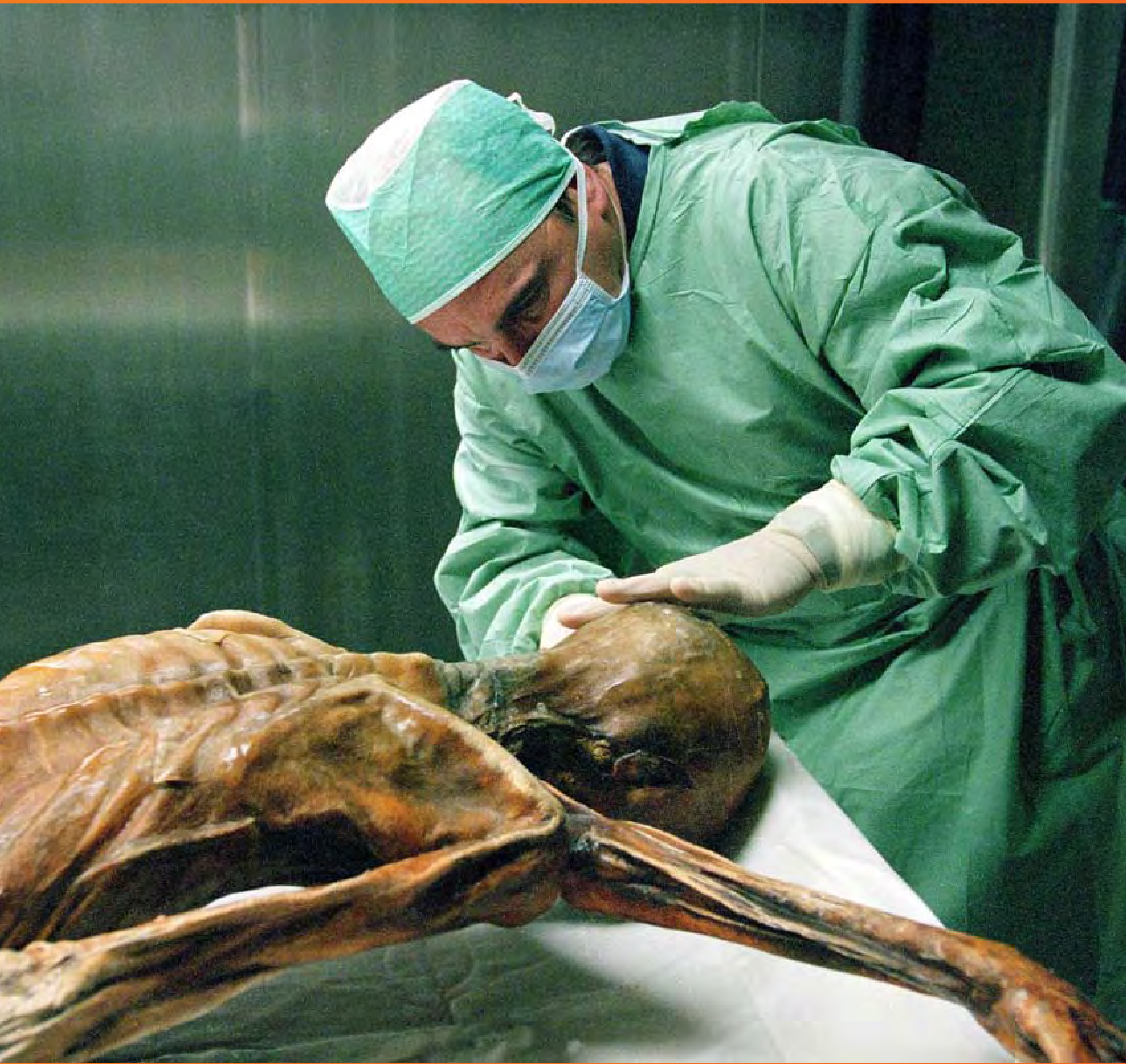
Nearly 100 AMS facilities now exist worldwide, one of them in Paris used by the Louvre museum, where experts use ion beams to examine age and characteristics of paintings, sculpture and artifacts without causing visible damage to the works themselves. The AMS facilities are based on small to medium-size accelerators, each collecting data from thousands of samples each year in various fields of science and technology.

Several features of particle accelerators contribute to the enormous sensitivity of AMS, in determining ratios of radioisotope to stable isotope concentrations as low as one in a quadrillion. The detection sensitivity of AMS for dating 50,000-year-old archeological artifacts with ^{14}C is equivalent to finding a single grain of sugar in a thousand three-story houses filled from cellar to attic with sugar.

Accelerator mass spectrometry measures concentrations of long-lived radioisotopes by counting atoms, rather than by detecting their radioactive decays. This leads to a huge gain in sensitivity, easily calculated for ^{14}C, for example, with a half life close to 6000 years. For contemporary carbon, a sample of one milligram yields about one radioactive decay per hour. During the same time, AMS accelerates and counts about one percent of the nearly one billion ^{14}C atoms in the sample, providing a million-fold increase in sensitivity.

Minimizing the sample size is of prime importance for rare archaeological objects, works of art or trace amounts of material. With AMS it is now possible to measure samples a thousand times smaller, in counting times 100 times shorter, than with conventional techniques. As a result, the dating of materials and related activities such as ocean water studies have seen exponential growth. The ability of the Woods Hole Oceanographic Institution's AMS facility to measure more than 10,000 half-liter water samples for ^{14}C, rather than the 250-liter samples and much longer measuring times previously needed, allowed researcher to generate three-dimensional detailed assays of this important tracer of ocean processes.

Oetzi, the Iceman, a unique and well preserved mummy from the end of the Neolithic period, discovered in the Alps in 1991. Radioisotope dating with ^{14}C established the age not only of the mummy but also of many often-minute artifacts associated with his equipment, clothing and food; and of flora and fauna at the site. ***Image courtesy of the South Tyrol Museum of Archaeology, www.iceman.it***



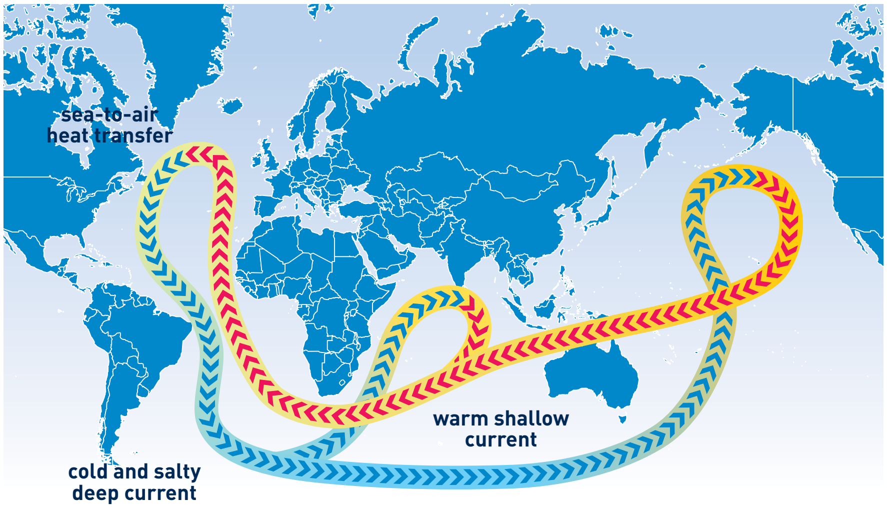
Several key aspects of accelerators confer AMS's immense sensitivity and selectivity. They include the filtering of beam species by the electromagnetic fields of the accelerator; eliminating molecules of the same mass by their break-up when traversing matter (a thin foil or gas) after acceleration; separating isobars, i.e. nuclei from a different chemical element but with the same mass, either by the use of selected ion sources or an energy-loss measurement at high energies. Finally, researchers can measure relative isotope yields with high reliability over the huge dynamic range of one in a quadrillion. This results from exactly counting individual radioisotope ions after acceleration in a particle detector, and precisely measuring the electric beam currents of the much more prolific stable isotopes.

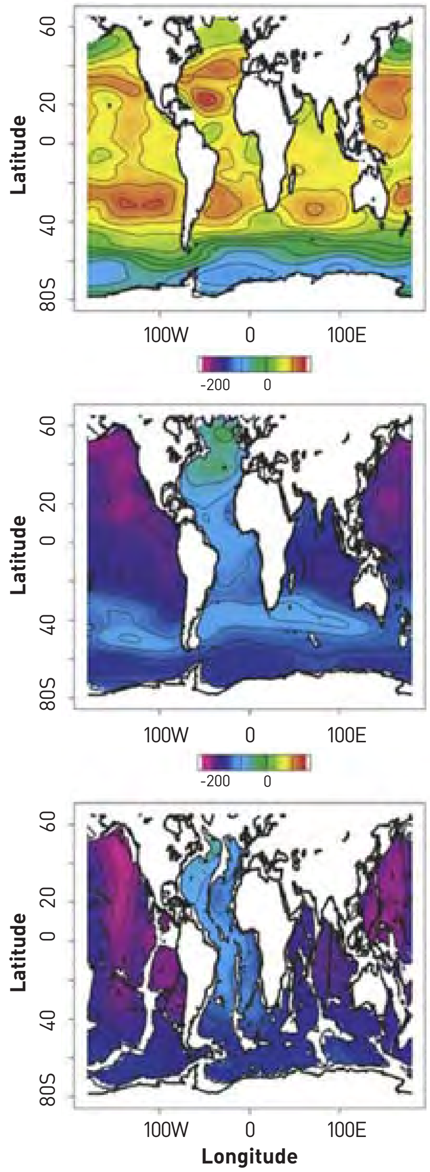
Because AMS counts the atoms of a radioisotope in a sample, the process is independent of the lifetime of the radioisotope. Accelerator mass spectrometry has established the use of more than 30 radioisotopes from various chemical elements, leading to an accessible lifetime range from about one year to ten million years. Most uses still involve ^{14}C. But ^{14}C measurements have substantially grown beyond archeology, the chronology of human expansion and the growth and decline of ancient civilizations. Using other important radioisotopes, such as ^{10}Be, ^{26}Al, ^{36}Cl, ^{41}Ca, ^{60}Fe, ^{121}I, ^{236}U and many others, researchers are applying AMS to a broad range of fields in geology, climate, medical and technological research.

These fields include the *atmosphere* with studies of trace gases, cosmogenic and anthropological radionuclides, origin and transport of aerosols, exchanges between atmospheric layers; the *hydrosphere* with dating of ground waters and aquifers, global ocean circulation patterns, paleo-climatic studies in lake and ocean sediments; the *cryosphere* with paleo-climatic studies of ice cores, variations of cosmic radiation, bomb peak identification; the *lithosphere* with exposure and erosion dating of surface rocks, tectonic plate subduction and volcanic rock measurements; the *cosmosphere* through radionuclides in meteoritic and lunar samples (and, perhaps, in the future samples from other planets), isotope ratios in presolar grains, supernova remnants on earth; and our technical world, the *technosphere*, with nuclear safeguards, neutron fluxes, forensic and *in vivo* tracer studies of plants, animals, and humans, with medical and pharmaceutical applications.

Environmental and climate studies have gained much attention due to concerns about natural versus anthropogenic causes of climate change. In this context, there is an unquestioned need for additional climate data to predict and respond to future climate trends, and AMS can make significant contributions.

Teams at research accelerators in the U.S. and Canada conceived and developed AMS. While they initially used existing nuclear physics facilities, by 1980 the growing interest in AMS led to the manufacture of smaller accelerators specifically dedicated to AMS. The trend to more compact facilities has continued, although several larger accelerators remain at the forefront of AMS. Of today's nearly 100 AMS facilities, at least two-thirds are now dedicated to AMS alone. An often close contact between AMS research groups and industry, across borders and continents, results in the rapid translation of research innovations into commercial products. While this partly reflects the limited size and cost of the accelerators, which facilitate industrial development of research instrumentation, it also offers a prime example of good and effective collaboration between research laboratories and the commercial sector.





The ocean plays an important role in the carbon cycle on seasonal to millennial time scales. The indications of recent global climate change and the questions about how it relates to human activity have led to increased carbon cycle research. Predictions about the influence of anthropogenic greenhouse gases on future climate rely on numerical models, and the accuracy of such predictions depends on reliable data. Over the last decades, broad-ranging studies via ocean sampling expeditions have provided extensive data on ocean properties and processes and on our understanding of ocean chemistry and biochemistry. In addition to the more commonly measured temperatures, salinities, oxygen, and nutrients, measurements of great importance to the ocean carbon cycle include total dissolved inorganic carbon, alkalinity, stable carbon-isotope ratios and the transient tracers tritium and radiocarbon, ^{14}C.

Conventional radiocarbon dating has been augmented by accelerator mass spectrometry, which allows sample sizes smaller by more than a factor of one hundred. The dedicated AMS facilities at the Woods Hole Oceanographic Institute have provided for measurements of nearly 20,000 samples. The figure above shows the great ocean conveyor belt illustration by Broecker which is a simplified picture of the ocean's main currents. The figures to the right show, from the top, contour maps of ^{14}C concentrations at the ocean surface and at 1200m and 3500m depths. The surface distribution is strongly influenced by uptake of bomb-produced ^{14}C. The deep ^{14}C reflects the aging of water; the conventional radiocarbon age ranges from ~400 years in the northwest Atlantic to ~2200 years in the subtropical to subpolar North Pacific. *Above image: Sandbox Studio; Image at right courtesy of R.M. Key, Princeton University*

Accelerators for Security and Defense

From the earliest days of their development, accelerators have made critical contributions to the security and defense of the United States. During World War II, accelerators contributed directly to the separation of isotopes using industrial-scale accelerator mass spectrometry and provided facilities for defense-related nuclear physics research. The plutonium war effort relied heavily on Ernest Lawrence's 60-inch cyclotron at Berkeley. In turn, war-related research, most notably radar, found peacetime applications in technologies for accelerators.

Post World War II government support of accelerator research led to the global preeminence of U.S. accelerator-research facilities and technological expertise. Universities and national laboratories, including defense laboratories, developed increasingly powerful and sophisticated accelerators for basic and applied sciences. As early as 1949, the potential uses of accelerators for national security included the predetonation of critical nuclear devices, the deployment of antipersonnel weapons, the detection of contraband fissile materials, the identification of aircraft and the enrichment of nuclear materials. Lawrence and the Berkeley group developed prototype accelerators including a high-intensity linear accelerator, the Materials Testing Accelerator.

The current U.S. accelerator-facility infrastructure at the national laboratories is the direct legacy of the Atomic Energy Commission's postwar program. The Department of Energy defense laboratories, Livermore, Los Alamos and Sandia, have also pursued security-related accelerator technology. Induction linac technology, originally developed for accelerator-induced fusion, finds application in radiography, of direct importance to the nuclear weapons program. The Los Alamos Neutron Science Center, or LANSCE, provides important nuclear data. Both Livermore and Sandia pursued electron-beam-based technology for directed-energy weapons. The

Particle beams can scan shipping containers for contraband materials.
Photo: Merten

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Continued support for basic science and for accelerator R&D as a scientific discipline has great significance for national security and defense.

Defense Advanced Research Projects Agency, or DARPA, supported the exploration of the potential of accelerators for direct military applications at the Advanced Test Accelerator and the RADLAC I, the Radial Line Accelerator.

The Los Alamos-based Beam Experiments Aboard a Rocket, or BEAR, deployed the then-new radio-frequency-quadrupole, or RFQ, based LINAC. This experiment succeeded in producing a neutral particle beam in flight and generated data on these technologies for the Department of Defense Strategic Defense Initiative Organization, SDIO. Argonne National Laboratory pursued neutral-particle-beam research with the Continuous Wave Deuterium Demonstrator. The SDIO activities were noteworthy for joint laboratory and industry cooperation.

Early applications of accelerators to inspect nuclear fuels used commercial low-energy (tens of MeV) electron linacs to induce photo-fission reactions. These inspection technologies expanded to waste-drum assays in the 1980s and eventually to cargo inspections. The invention of the free electron laser in the 1970s led to ever-higher-power electromagnetic radiation using high-energy electrons, of direct interest to security and defense applications, including the Navy's proposed application of free-electron laser technology to shipboard defense.

Nearly all accelerator applications for security and defense have sprung from research and development in fundamental science. The promise of future accelerator technologies continues to rest on advances in basic science and its need for more and more powerful tools. These accelerator advances stock the shelves with technologies and data. The scientific and technical workforce engaged in these developments contributes to their application to security programs. Continued support for basic science and for accelerator R&D as a scientific discipline has great significance for national security and defense.

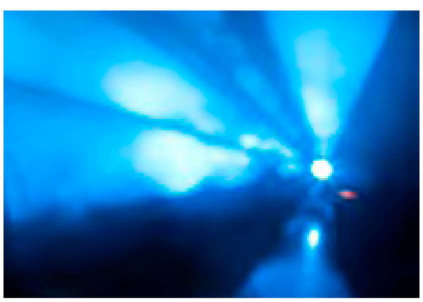


Photo: Reidar Hahn, Fermilab

NEEDS, OPPORTUNITIES AND TECHNOLOGIES

Accelerator technologies find applications for a diverse and growing set of security and defense needs, including stockpile stewardship, war-fighter and asset protection, materials characterization, interrogation of cargo and inspection capabilities of all types, and the support of present and future nonproliferation regimes.

Accelerator laboratories and technologies have the potential to make significant contributions to the needs of national security and defense in ten key areas: physical data; high-energy-density conditions; directed-energy capability; cargo inspection and interrogation; replacement of radioactive sources and materials; isotope production; nuclear forensics; compact, fieldable accelerator systems; simulation tools; and workforce training.

Physical data

National security and defense programs have a critical need for the highest-quality data on materials characterization, material alteration, nuclear fission, and the interaction of radiation with materials. These requirements rely on all the types of accelerator facilities operated by the DOE Office of Science: neutron sources, synchrotron radiation light sources, and low- and high-energy particle beams.

The data are necessary to reliably simulate systems for detecting special nuclear materials and byproducts of nuclear fission. Much of the current data is incomplete and much of it dates from the 1950s and 1960s. Missing data include time, angular, and neutron-gamma correlations; high-resolution spectroscopy; and nuclear resonance fluorescence. Existing accelerator facilities could perform this work, but often encounter impediments to conducting measurements with special nuclear materials. The facilities may lack licenses to hold such materials or may be unprepared for the associated health and safety requirements.

Obtaining these data will require particle- and nuclear-physics-style detectors with near full solid-angle coverage, particle identification, and fast timing. A significant challenge is the development of detectors that operate in ambient conditions. For example, many current detectors must operate at extremely low (tens of degrees Kelvin) temperatures. Developing materials that can operate in ambient conditions while accurately recording events is a great challenge for security and defense field operations.

A further challenge is to develop dedicated accelerator-based beamlines, for example a beamline at a synchrotron light source, for security and defense needs. Currently, the nation has no dedicated beamline for studies of exotic materials including radiological, biological, chemical and explosive ones. Accelerator-based science has much to contribute to better production of such materials, characterization of their reactions, decontamination and safer handling.

High energy density

Facilities that provide conditions of high energy density, such as those found in plasmas, provide an important, controlled environment for understanding phenomena important to aspects of the security mission. Many such pulsed-power based facilities have operated outside the DOE Office of Science mission. However, accelerator research for inertial confinement fusion concepts could advance such high-energy-density environments and serve high-energy-density research for security and defense.

Directed energy

Accelerator-based directed-energy capabilities have been pursued from the earliest times of accelerator development. Research into beam-power levels high enough for directed energy has supported the development of several technologies, most notably radio-frequency-quadrupole structures, or RFQs,

Accelerator technologies find applications for a diverse and growing set of security and defense needs, including:

- ***stockpile stewardship***
- ***war-fighter and asset protection***
- ***materials characterization***
- ***interrogation of cargo***
- ***inspection capabilities of all types***
- ***the support of present and future non-proliferation regimes.***

now ubiquitous in the accelerator world. The current need is for development of a fieldable device for testing with defense and security partners.

Relativistic electron beams can generate high-power electromagnetic radiation at various frequencies for directed-energy-specific missions. Examples include free electron lasers, highly directional gamma-ray beams through Compton scattering, and millimeter-wave to terahertz radiation.

Accelerators are central to a number of current proposals to develop cargo-inspection techniques.

Free electron lasers can in principle achieve megawatt average power levels and optical beam quality and wavelengths required for security and defense purposes. In the mid-1990s, the highest average-power FEL had achieved only 11 watts. The Navy, as a user of the FEL at DOE's Thomas Jefferson National Accelerator Facility achieved 2.2 kW, and a subsequent upgrade in 2006 demonstrated 14kW at 1.6microns, a wavelength of particular interest to the Navy.

Free electron laser-based directed energy can expand to a wide range of missions. With increased efficiency and decreased weight, for example, FELs might serve as airborne platforms. With appropriate R&D, such goals appear achievable. Most such improvements would feed back to the basic science programs, potentially leading to lower-cost FEL systems and associated energy-recovery-linac light sources.

A megawatt-class FEL will require several critical accelerator R&D developments. Credible designs exist for two of these: a high-quality ampere-class electron gun and continuous wave injector that can operate for weeks, and ampere-class SRF cavities with higher-mode suppression using high-temperature superconductors. However, demonstration of these designs requires funding. At the conceptual level with simulations, researchers are currently exploring a third critical element, megawatt-level RF couplers. Complete system modeling is underway; but bringing these efforts to the point of comparison to the actual performance of, for example, future 100-kW prototypes, will require major efforts.

Computer animation of the field inside a superconducting accelerator resonator
Image courtesy of DESY

Cargo inspection and interrogation

Security priorities of the last decade have turned to deterring the threat from subnational organizations. Some of these deterrents rely on identifying small quantities of special nuclear material in shipping containers through a signature reaction induced by radiation. Accelerators are a natural choice for producing well-characterized beams of radiation and are central to a number of current proposals to develop active interrogation techniques.

"Standing off" at a distance from the object under inspection by using electromagnetic radiation, including that from accelerators, is of significant interest in security and defense. The recent developments in terahertz radiation at FELs show potential for active interrogation with desirable standoff distances for cargo, improvised explosive devices and biological investigations.

Other interrogation techniques use neutron and proton beams ranging from tens of keV to tens of GeV with radiographic sensitivity to a variety of materials. Standoff with GeV protons to induce fission will require milliampere beam currents, high gradient and high temperature superconducting technologies, as well as compact devices that laser-driven accelerator technology may make possible.

Researchers have proposed more exotic radiography using the low interaction rates of muons to achieve significant standoff. Such proposals would build on developments for muon colliders and neutrino factories, the subject of R&D for possible future basic-science facilities.

Replacement of radioactive sources and materials

In the 1970s, accelerator-based gamma-ray radiation therapy replaced radioisotope-based devices in the United States and Western Europe. However, in much of the rest of the world, ^{60}Co-based teletherapy units are still very common, with over 10,000 in service, according to the International Atomic Energy Agency.

With an average radioactivity of 2000 curies, these devices represent a potential source of material for a radiological attack. Progress towards more compact, rugged, and reliable accelerators can replace ^{60}Co-based sources in medicine, as well as in industrial applications.

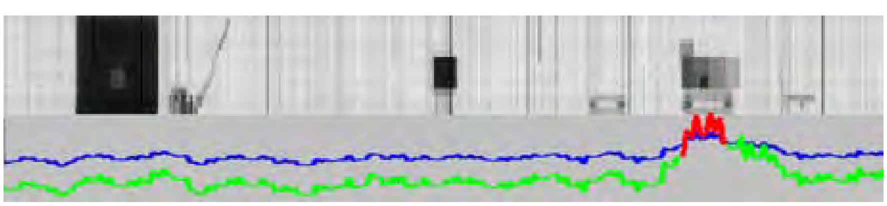
Advances in high-gradient accelerator structures, microwave generation, and power electronics could sharply reduce the cost of accelerator-based therapy. The accelerator must be able to function with high reliability in adverse environmental conditions, with fluctuating electrical supply. Because it is unlikely that private industry would undertake such a design without a defined market, deployment of this accelerator would need to be a coordinated effort among various U.S. government agencies, industry and the international community.

Isotope production

Accelerator production of both stable and radioactive isotopes has potential impact on security and defense. Demand for the stable helium isotope ^{3}He has significantly increased in recent years, due to its use in neutron detectors for portal monitors and other systems for detecting special nuclear materials. The main source of ^{3}He is as a byproduct of the nuclear weapons stockpile. Changes in stockpile management have led to decreased production, creating a need that accelerators could meet. Beyond security, researchers in low-temperature physics and materials science are suffering severely from the shortfall in ^{3}He.

Production of the medical isotope ^{99m}Tc by reactor irradiation of a nuclear material (^{235}U) yields the same by-products as detonation of a nuclear device. As part of the Comprehensive Test Ban Treaty, monitoring stations worldwide look for telltale by-products, specifically for the radioactive isotopes of the noble gas xenon that are difficult to contain and that propagate over large distances in the atmosphere. Medical isotope production affects the sensitivity of radio-xenon measurements by producing elevated and variable concentrations over large areas around production facilities. Accelerator-based production at required volumes and competitive costs would reduce backgrounds, enhance international monitoring capabilities, and simultaneously eliminate the need for highly enriched uranium and nuclear reactor facilities for production.

Accelerator production of both stable and radioactive isotopes has potential impact on security and defense.



Neutron counts　Alarm threshold　Alarm condition

Detection of neutrons from accelerator-induced reactions with cargo materials reveals the presence of fissile materials.
Image courtesy of Idaho Accelerator Center

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A clear need exists in a variety of security and defense applications for compact, robust, high-gradient accelerator systems that can be deployed in the field.

Nuclear forensics

Currently nuclear forensic analyses require intensive and time-consuming chemical separations using laboratory-grade mass spectrometers and other analytical instruments. Reducing the time required for these analyses and moving the instrumentation to a field-deployable laboratory would have significant advantages. A fundamental limitation of mass spectrometers that drives the need for chemical separations is the limitation in dynamic range, that is, the ability to detect trace constituents in the presence of large amounts of other constituents. Underlying accelerator technologies could lead to order-of-magnitude increases in dynamic range. The capacity to operate in field conditions will, however, require significant improvements in reliability and ruggedness.

Compact, fieldable accelerator systems

A clear need exists in a variety of security and defense applications for compact, robust, high-gradient accelerator systems that can be deployed in the field. Currently, vibrations and temperature swings affect most accelerator-based technology, and components and infrastructure occupy a large space. All of these components require integration into a single compact unit that can withstand the challenging environments associated with field use, and that a layman can operate. This is especially critical for the forensics area of security and defense, where detection, characterization, and decontamination operations need to occur quickly.

The requisite accelerator R&D ranges from activities that overlap with frontier research in basic science, such as superconducting radio-frequency, x-band, and plasma wakefield accelerators, to technologies such as inverse free electron lasers and types of induction accelerators currently not pursued in physics research. Compact systems will need high energy-recovery efficiency to minimize power consumption. The development of improved materials for superconducting technologies is also important.

Rugged, reliable, fieldable accelerator systems will also benefit from innovation in high-power radio-frequency systems. The ideal endpoint of this research might be an all-solid-state accelerator radio-frequency system. Compact accelerators will need reliable high-current, high-brightness particle sources, calling for development of photocathodes for electron beam sources.

Simulations tools

The security and defense sector relies on numerical modeling codes such as GEANT, MCNP and GADRAS with origins in high-energy and nuclear physics. These codes require continuous maintenance, validation and adaptation to evolving computing architectures. As new data emerge from experimental physics, it is critical to update and validate the underlying physics processes and nuclear data that these codes use. Security and defense applications often include sets of requirements different from most of the mainstream application of the available codes, leading to limitations in the underlying physics models and data.

Nearly all modern accelerator projects, including those for security and defense applications, use extensive numerical simulation analyses to optimize designs and to reduce cost and risk. Many of the tools in use today are based on work developed in the 1970s and 1980s on computer mainframes. However, the last decade has seen a shift to massive parallel systems with tens to hundreds of thousands of processors.

The SciDAC program has provided some support for advanced accelerator code development, but many if not most of the tools developed in those research programs have not trickled down to the broader accelerator science community or to industry. In some cases the problem is lack of user friendliness and communication. In other cases the codes remain state-of-the-art works in

Cargo Scanning

More than two billion tons of cargo pass through United States ports and waterways annually. The current method of checking this cargo for radioactive materials or weapons uses x-rays scanners, like the machines used at security checkpoints in airports. According to a growing group of scientists, particle beams from an accelerator may offer a more effective solution for identifying radioactive material in cargo to keep ports safe and prevent contraband from entering the country.

X-rays reveal the basic shape of the cargo inside a container, but they cannot provide detailed information about the material it is made of and whether, for example, it is radioactive.

"X-rays work with density. If something is denser, it lets fewer x-rays through," said Ed Hartouni, a physicist at Lawrence Livermore National Laboratory. "With x-ray technology, you can't tell the difference between, say, an engine block and the core of a nuclear weapon core. If you're a clever smuggler, you'll be able to hide the shapes of contraband."

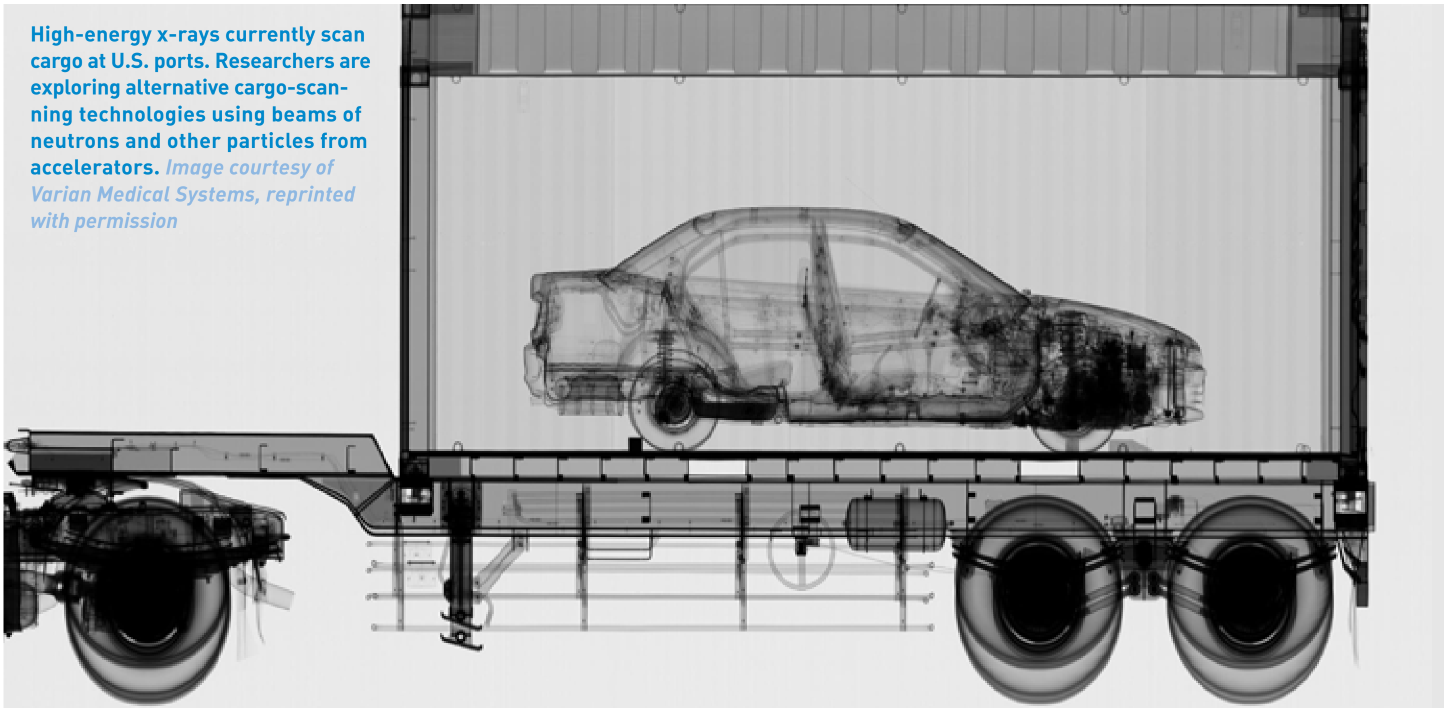
Any material that contains a radioactive isotope emits a particular kind of radiation, a kind of signature. A particle accelerator can allow cargo scanners to recognize the signature it gives off. "It gives you eyes to see the very things you want and not be confused," Hartouni said.

Multiple national laboratories and universities are currently researching the ability of particle accelerators to scan cargo. A pulse of neutron particles, for example, would illuminate the items inside the cargo and react with the nuclei, which then emit gamma rays. A particle detector would identify the type of gamma ray and reveal what is inside the box.

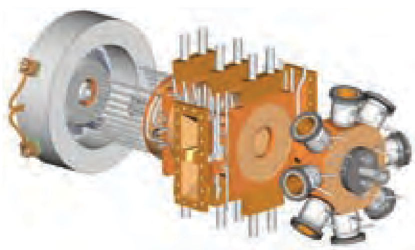
Another idea would use cosmic rays, naturally occurring particles that travel through space. By measuring how the particles scatter, scientists could use cosmic rays to paint a picture of what is inside the cargo container. More than just an outline that a typical x-ray scanner would provide, the cosmic rays could reveal the isotopic structure, or an elemental map, of any radioactive materials.

Scientists are currently working to develop compact accelerators that would be practical and effective to use in a port. These particle scanners are not yet available on the commercial shelf, but some small businesses are collaborating with national laboratories to develop these cargo-scanning technologies.

High-energy x-rays currently scan cargo at U.S. ports. Researchers are exploring alternative cargo-scanning technologies using beams of neutrons and other particles from accelerators. *Image courtesy of Varian Medical Systems, reprinted with permission*



progress, without sufficient benchmarking or dependability testing. Code development and the constant adaptation to computer architecture and computing power require a concerted effort.



A high-average-current gun for injecting electrons into an accelerator *Image courtesy of Analytical Research LLC*

Pulsed power needs and applications

To produce the extreme environments relevant to various aspects of nuclear weapons science—both the underlying physics of nuclear weapons and the radiation technology—accelerator scientists have developed pulsed-power accelerators with impressive characteristics: peak beam power up to 100 terawatts, pulse energy up to 25 megajoules and peak beam currents up to 30 mega-amperes. The extreme conditions produced by these accelerators have dictated a single-shot mode of operation; the time to clean and reconfigure the load region means that the machines can only be fired a few times a day.

Researchers have used induction accelerators, with their inherent capability to handle kiloampere beams, to assess the feasibility of propagating charged-particle beams through the atmosphere for missile defense, to drive free electron lasers from 8 mm down to 10.6 microns, and to produce flash x-ray sources for radiography. The design and construction of several large machines have produced many significant accelerator innovations, including, among others, the development of modulaters to power a fast kicker that took the first-ever radiographic "moving picture" of a weapon implosion.

The recent development of the dielectric wall accelerator, a coreless induction accelerator, promises accelerating gradients on the order of 100 mega-volts per meter for short pulses. High-gradient switches will lead to more compact accelerators, result in more compact pulsed-power sources and have security and defense applications such as variable-frequency high-power microwave sources. This technology would also enable single-room proton therapy systems for cancer, transportable GeV proton accelerators for active standoff detection, and small electron accelerators for Compton sources and free electron lasers. Key R&D areas involve development of insulators, dielectrics, solid state switches, and diodes.

Existing or planned machines meet most of the needs for nuclear weapons science, although the NNSA stockpile stewardship mission would benefit from doubling of accelerator current to 60 mega-amperes. These accelerator architectures would build upon new high-current versions of linear-transformer-driver, or LTD, technology. Pulsed-power machines may be the preferred compact accelerator technology where radiographic detection of special nuclear materials and other security and defense applications require kilo-ampere currents and modest voltages (1-20 MeV). Pulsed-power machines for dynamic material compression, jointly supported by the NNSA and the Office of Science, could be an ideal technology for overlapping pulsed-power capabilities with light source facilities for examining materials under extreme conditions.

The pulsed-power community has begun to engage emerging customers in the areas of intelligence, nonproliferation, and nuclear counter-terrorism. They are defining the requirements for broader security and defense applications and the intersection of pulsed-power capabilities with these requirements. The relative compactness, efficiency, and high-output radiation of pulsed-power systems are attractive, but the single-shot operation is a severe limitation for many applications. Meeting the emerging needs of this community will require significant technology development in pulsed-power systems. The effort may also increase the overlap with the underlying accelerator technologies of the DOE Office of Science research programs.

Radio-frequency and advanced accelerator technologies

Recently, national and international collaborations have stimulated research to study the limits of room-temperature linacs, leading to the doubling of the usable gradient in normal-conducting high-gradient linacs. The emerging technologies fostered by this research effort hold the promise of a broad, transformational impact.

Beams of protons with energies greater than 1 GeV can pass through distances of a few kilometers without appreciable losses. A particle accelerator on a ship or military aircraft could produce such charged particles and direct them at objects of interest at standoff distances of more than 1 km. Protons at these energies generate large showers of charged and uncharged particles, which propagate through an object under inspection. To detect special nuclear materials, detectors monitor delayed neutrons and gamma rays.

Because of the need for exploration into these energies and the need for high efficiencies, techniques such as superconducting radio-frequency, plasma and other wakefield acceleration techniques, and other high-gradient acceleration concepts have come under consideration.

POLICY CHALLENGES

Current impediments to accelerator innovation in the security and defense program include weakness in the development of the scientific, engineering and technological work force for accelerators; lack of communication and coordination among stakeholders; the lack of funding for appropriate accelerator R&D; and aversion to risk.

The scientific, engineering and technical work force

The lack of early-career scientists in the field of basic accelerator R&D is worrisome, especially in the context of the aging current workforce. Determining the workforce needs of the security and defense application areas is critical for developing the appropriate accelerator R&D. Encouraging U.S. citizens to join accelerator programs is imperative.

A large fraction of the scientific and engineering work force in accelerator-based security and defense science and investigation received early training or had their first professional positions in fields supported by physics research. The replacement work force has significantly shrunk due to an unfortunate confluence of factors. Few engineering and physics departments in U.S. universities offer courses, much less graduate degrees, in accelerator-oriented science. Very few early-career faculty and post-doctoral scientists in U.S. universities receive significant support directly tied to security-and defense-oriented accelerator science, nor is there a strong summer program to expose young scientists and engineers to needs and opportunities in the field.

To stop this erosion, based upon security and defense needs alone, there is a need for stakeholder agencies to improve funding for graduate students, post-doctoral scientists and early career faculty in accelerator-related fields. Support for particle accelerator schools, such as the U.S. Particle Accelerator School, also helps to address this shortage of trained accelerator scientists and engineers. Agency-funded summer workshops on accelerator-related topics offer another possibility for developing collaborations between universities and security-oriented accelerator science. The Directed Energy Professional Society offers competitive internships and scholarships for students based on grants from funding agencies. Coordination among accelerator schools and programs could further enhance accelerator education for national security and defense.

A very significant pay disparity exists between the field of accelerator science—and many other areas of basic science—and industry. The only long-term solution to avert a crisis associated with recruiting and retaining a talented, young and energized workforce is to offer salaries that are competitive with

Encouraging U.S. citizens to join accelerator programs is imperative.

University of Chicago scientist Rafael Jaramillo and Argonne scientist Yejun Feng examine the element chromium at the Advanced Photon Source. Studying simple metallic chromium, the joint UC-Argonne team has discovered a pressure-driven quantum critical regime and has achieved the first direct measurement of a "naked" quantum singularity in an elemental magnet. ***Photo: Argonne National Laboratory***

Students at Fermilab
Photo: Reidar Hahn, Fermilab

A significant challenge is the limited interaction between the security and defense and the accelerator science communities.

Poster session at the Accelerators for America's Future Symposium *Photo: Reidar Hahn, Fermilab*

industry and other fields. This single step would not only encourage young people, especially U.S. citizens, to enter the field, but would provide a competitive environment to retain the very best engineers and scientists.

Communication and coordination

A significant challenge to the use of accelerators for security and defense is the limited interaction between the security and defense and the accelerator science communities. For example, the DOE Office of Science has successfully supported basic research in accelerators, partly through SBIR/STTR programs. These programs can play a significant and useful role in the transfer of accelerator knowledge to other agencies including the Department of Defense, the National Institutes of Health, the Department of Homeland Security and NATO. However, the lack of coordination among the SBIR/STTR programs in the different agencies impedes this transfer of progress.

The development of muon technology for active interrogation provides a case in point. Interagency cooperation would facilitate the efficient transfer of accelerator knowledge that high-energy physics researchers have developed for future energy-frontier muon colliders. Now that DOD and DHS are actively funding studies of muon generators for the standoff detection of special nuclear materials, it makes eminent sense to apply the expertise already developed to this new security and defense concept.

Another barrier to collaboration is the difference in the way the two communities manage data. The accelerator science community traditionally publishes in scientific journals, while the security and defense community keeps this information secret.

Funding

Funding for continued accelerator R&D is critical for supporting future programs in security and defense. For the most part, innovative accelerator technologies have emerged from basic science research at the energy frontier. Often, decades later, these technologies find important applications in national security and defense, a process that cannot happen without the continuing development of innovative, and therefore risky, ideas. The Department of Energy's accelerator R&D program, with major funding provided in the past by the Offices of High Energy Physics and Nuclear Physics has been a major source of those innovative ideas.

The short-term nature of the federal funding cycle for large-scale projects creates a barrier to developing a joint accelerator community. The budgetary uncertainty makes project planning, staff retention and collaboration difficult. Another issue is that scientific projects are often funded for parts of the proposed program. Partially funded projects never achieve the full range of initial goals, stifling progress in a given area. Progress depends on making full funding a priority.

Bridging the gap from research to deployment

Bridging the "valley of death," the crucial stage of a technology between the initial idea and scientific prototype and the deployment of a commercially fabricated product, will require a conscious, concerted effort to integrate the accelerator R&D program across the many stakeholder departments and agencies. Personnel should receive encouragement and recognition for working with industry in the effort to transfer technology and knowledge. Long-range planning, technology road-mapping, and technology implementation plans will need to include the full community of potential users. To succeed, such a program must acknowledge the risk inherent in developing innovative, compact, efficient, self-shielded accelerators. Opportunities involve risk; the low tolerance for risk in the current research culture constitutes a major challenge for realizing the opportunities of accelerator technology.

FINDINGS

The applied-science applications of the security and defense program rest on advances in basic science, specifically in the area of accelerator research and development.

There is a great need either for increased access to existing advanced scientific facilities or for commissioning new facilities, or both, to generate physical data on materials critical to the security and defense programs. These facilities include accelerators, synchrotron radiation light sources and neutron sources to characterize chemical, biological, explosive and nuclear materials.

Accelerator R&D for security and defense depends on a scientific and technical work force trained at DOE Office of Science accelerator laboratories, universities and educational institutions, and at dedicated accelerator schools.

An integrated national program is critical for realizing the challenges of future security-and-defense-related accelerator R&D.

The future direction of security and defense accelerator R&D is towards compact accelerator systems—low cost, small size, energy efficient, rugged, high reliability, high performance—of all types. Mapped onto the overall accelerator R&D landscape, these characteristics take advantage of advances such as high-gradient acceleration schemes, energy recovery technology, and innovative radio-frequency systems.

Applications of accelerators for security and defense have a particular need for updated and improved simulation tools.

An external panel of independent expert reviewers from outside the security and defense accelerator R&D stakeholders would have great value to both project scientists and funding agencies in bringing fresh and original perspectives and identifying pathfinding approaches to technology and policy challenges relevant to security and defense accelerator R&D.

An integrated national program in accelerator R&D that includes all stakeholders is critical for realizing the challenges of future security-and-defense-related accelerator R&D.

The Accelerators for America's Future Symposium in Washington, DC
Photo: Reidar Hahn, Fermilab

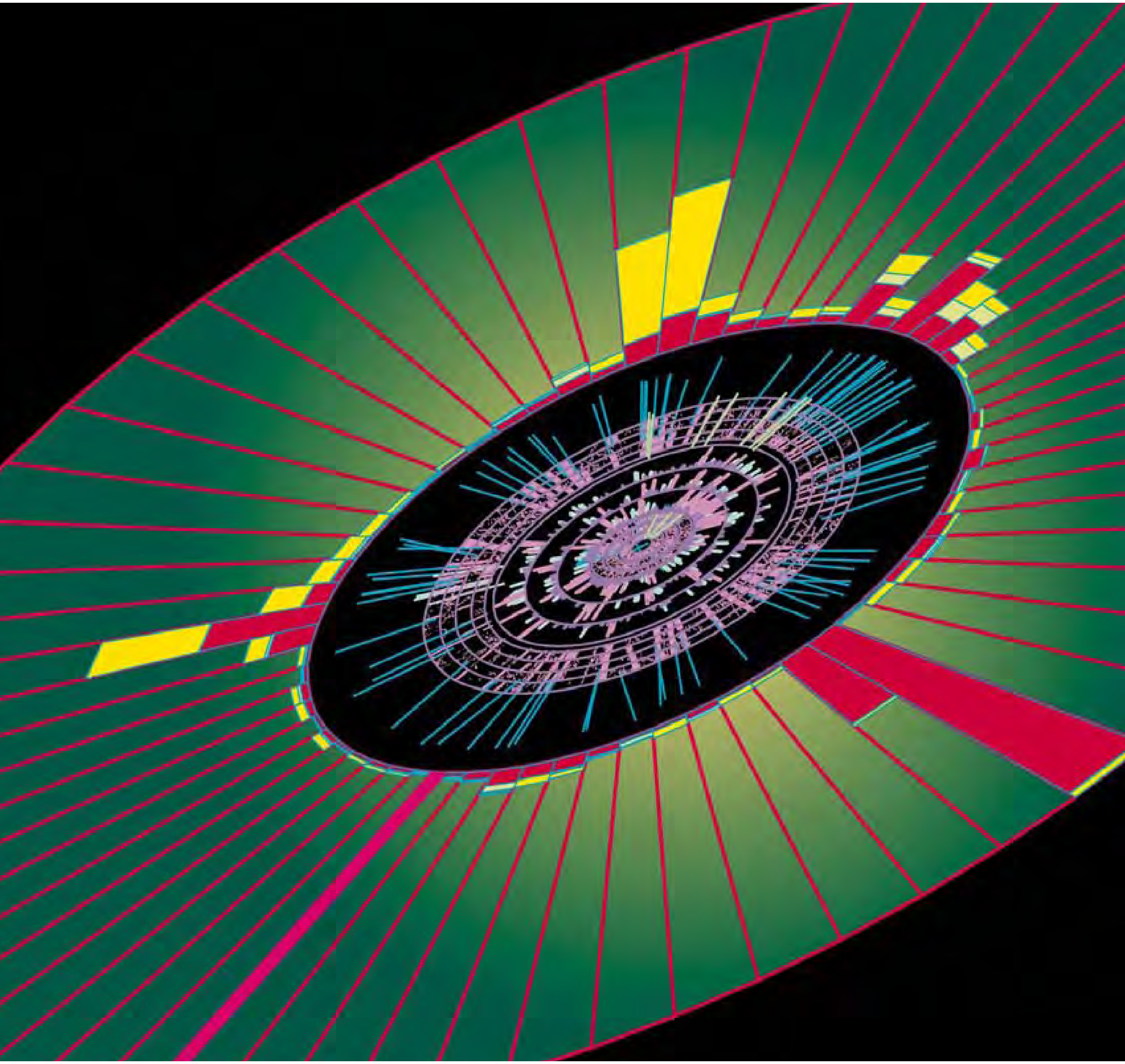
Attendees at the symposium
Photo: Reidar Hahn, Fermilab

Accelerators for Discovery Science

Discovery science searches for answers to the fundamental questions about the world and the universe around us. What are the laws of nature that explain its beauty and mystery at every level, from the simplest building blocks to the most complex forms of life? Throughout human history, scientific inquiries of ever increasing power and sophistication have addressed these basic questions, leading to revolutionary insights into the nature of the world and transforming human civilization. Scientific progress depends on the development of powerful investigative tools, from Galileo's telescope in 1609 to the most sophisticated instruments today. The National Academy of Engineering lists "to engineer the tools for scientific discovery" among its "Grand Challenges for the 21st Century."

From the earliest days of their development in the 1930s, researchers have brought their bold and innovative particle accelerator technologies to a broad range of fields of discovery science, with extraordinary success. When Ernest Lawrence built the first cyclotron in 1930 at Berkeley, California, it had an energy of 80 thousand electron volts and a diameter of 4 inches. Lawrence could hold it in his hand. With a circumference of 16 miles, today's most powerful particle accelerator, the Large Hadron Collider at Europe's CERN laboratory, will ultimately have an energy of 14 trillion electron volts. In between have come countless intermediate machines and remarkable advances in every aspect of accelerator technology. Each generation of particle accelerators builds on the achievements of the previous ones, raising the level of technology ever higher. Today, particle accelerators are essential tools of discovery for particle and nuclear physics and for sciences that use x-rays and neutrons.

A pair of top quarks reconstructed from a proton-antiproton collision in the DZero experiment at Fermilab's Tevatron. *Image courtesy of Fermilab*



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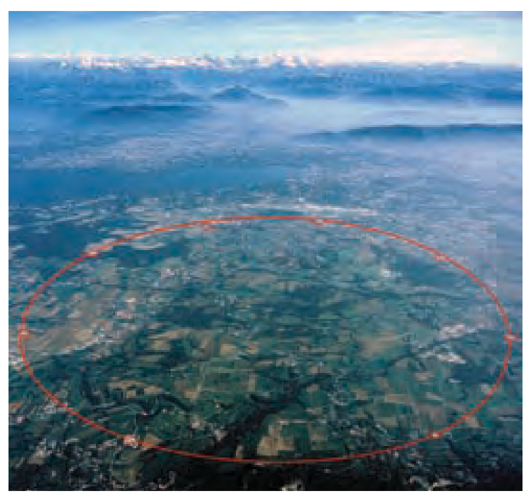
Today, American leadership is challenged as other nations seize the opportunities to develop and apply accelerator technologies to 21st-century challenges.

Nuclear physics investigates how the fundamental building blocks from the big-bang plasma combine to make nucleons and complex nuclei, how the chemical elements are formed in astrophysical processes, and how their interactions power the sun and the stars. Particle physics asks questions about the fundamental nature of the physical universe: What are matter and energy, space and time? X-ray and neutron-based science investigate the nature of the physical world at the atomic and molecular level, taking in the vast territory of chemistry, physics, materials science, biology and medicine, earth science and the engineering sciences. Accelerator science explores particle beams themselves: their character and interactions and how to generate and manipulate them.

The United States has been prominent in particle accelerator technology from early on, and American science has led the field not only in accelerator development but also in the sciences that use accelerators as tools. Today, that leadership is challenged as other nations seize the opportunities to develop and apply accelerator technologies to 21st-century challenges. Worldwide, the uses of accelerators are evolving rapidly, but in the U.S., many important aspects of the science and technology of accelerator development have struggled to keep pace with opportunity and demand.

Ernest Lawrence's first cyclotron *Photo courtesy of symmetry magazine*



The Large Hadron Collider at CERN, in Geneva, Switzerland *Photo courtesy of CERN*

Nuclear Physics

Visible matter in the universe—the matter that makes up stars, planets, life—has existed for billions of years. Through research in the past few decades, we have begun to understand the mysteries of its origin, evolution, and structure. Nuclear physicists investigate how the fundamental building blocks of the big-bang plasma form nucleons and nuclei, how astrophysical processes create the chemical elements, and how interactions between them power the sun and the stars.

Over more than half a century, researchers have developed unique accelerator technologies and tools to address the mysteries of nuclear physics. The very first accelerators of the 1930s were built to explore the properties of the atomic nucleus. In 1927, Lord Rutherford, the discoverer of the nucleus, asked for a "copious supply" of particles with more energy than the naturally occurring alpha and beta particles he had to work with at the time. "What we require," Rutherford said, "is an apparatus to give us a potential of the order of 10 million volts which can be safely accommodated in a reasonably sized room…I see no reason why such a requirement cannot be made practical."

The accelerators that followed not only probed the mysteries of matter but have also led to many economic and practical benefits for society. The U.S. has long played a leading role in this field, and with the appropriate investments the nation can continue as a leader in the future. Recent advances in accelerators from nuclear physics include: polarized and multi-charge state ion sources; beam cooling; superconducting radio-frequency acclererators for ion and continuous wave (polarized) electron beams; superconducting cyclotrons; and heavy-ion beams, up to maximum collision energies between particles of close to 40 TeV in gold-on-gold. In the 1990s, the Department of Energy completed two flagship accelerator facilities for nuclear science, the Continuous Electron Beam Accelerator Facility, CEBAF, at Thomas Jefferson National Accelerator Facility, or TJNAF, and the Relativistic Heavy Ion Collider, or RHIC, at Brookhaven National Laboratory. Experiments at TJNAF have significantly deepened our knowledge of the fundamental force called the strong interaction and how it defines atomic nuclei. The hot dense matter created in RHIC's gold-gold collisions has revealed traits of the deconfined quark-gluon matter that made up our universe shortly after the Big Bang, and has recently shown hints of bubbles of profound symmetry transformations in the hot soup of quarks, antiquarks and gluons.

NEEDS, OPPORTUNITIES AND TECHNOLOGIES

Building on the foundation of the recent past, nuclear science in the U.S. focuses today on three broad but highly related research frontiers. The first explores the theory of the strong nuclear interaction, quantum chromodynamics, called QCD, and its implications and predictions for the matter in the early universe; quark confinement (the absence of free quarks); the role of gluons; and the structure of the proton and neutron. At TJNAF, an energy upgrade of the electron beam to 12 GeV is already underway. It will definitively establish the contribution of valence quarks to hadron structure. The role of the gluons, the carriers of the strong force, in determining the properties and structure of strongly interacting matter is the major focus for future research beyond TJNAF and RHIC in nuclear physics. The nuclear physics community is discussing the need for a high-energy electron-ion collider, or EIC, as a gluon microscope.

The second research frontier investigates the structure of atomic nuclei and nuclear astrophysics. It addresses the origin of the elements, the limits of nuclei, and the evolution of the cosmos. The major technical requirement is

Nuclear physics investigates how the fundamental building blocks of the big-bang plasma form nucleons and nuclei, how astrophysical processes create the chemical elements, and how their interactions power the sun and the stars.

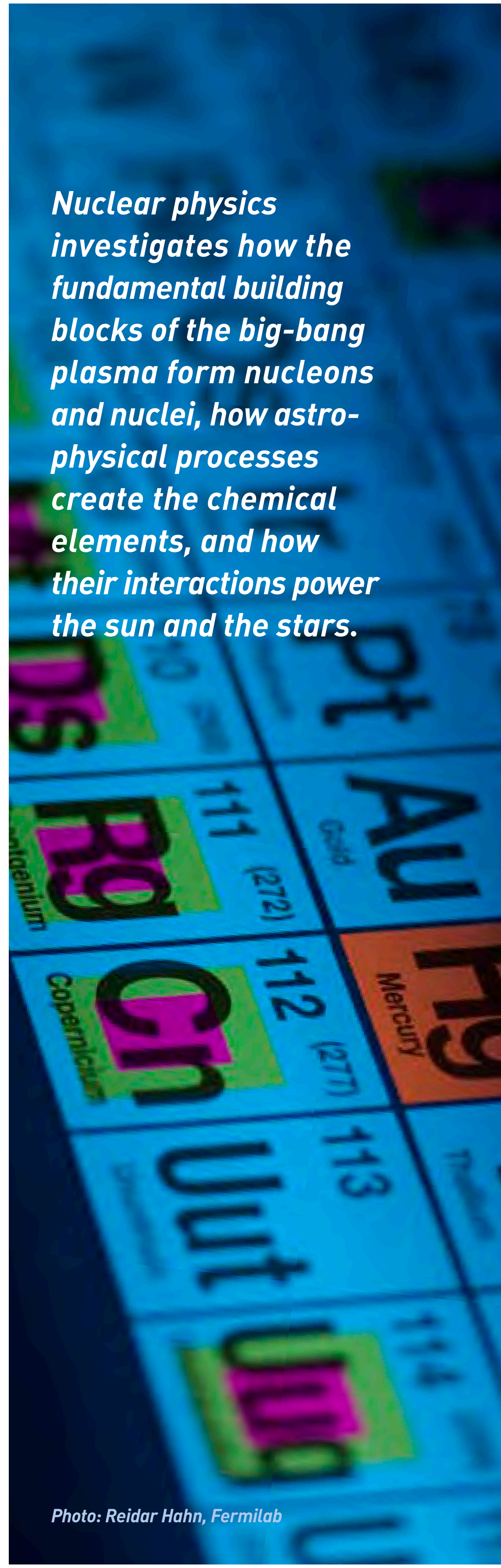


Photo: Reidar Hahn, Fermilab

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Each area of nuclear physics research will require advanced accelerator capabilities.

the creation of significant quantities of short-lived nuclei far from stability. The Facility for Rare Isotope Beams, or FRIB, now under construction at Michigan State University will produce such new isotopes in abundance.

Developing a New Standard Model of nature's fundamental interactions and understanding its implications for the origin of matter and the properties of neutrinos and nuclei is the third frontier. Nuclear physics research focuses on unique scientific opportunities at the low-energy precision frontier. Future accelerators will be important sources of neutrinos for investigating the fundamental interactions of these mysterious and ubiquitous particles.

TECHNICAL CHALLENGES

Each of these three areas of research will require advanced accelerator capabilities. For the electron-ion collider, major challenges include development of high-intensity energy recovery linacs, techniques to cool high-energy hadrons for increased luminosity, intense sources of polarized electrons and ions, as well as understanding of beam-beam effects. The major accelerator challenges for rare isotope beam facilities include high-intensity ion sources and high-power superconducting radio-frequency, or SRF, accelerators for the intense primary production beams, and high-power charge-state strippers and target set-ups. The neutrino beams require significant development of intense proton beams at multi-GeV energies. Development of high-intensity, high-power, low-beam-loss SRF accelerators is a common thread for accelerators in science.

For the beam cooling of high-energy hadron colliders, coherent electron cooling and optical stochastic cooling are promising techniques. Each requires development of technologies such as high-intensity, high-brightness energy recovery linacs and high-gain, high-power optical amplifiers. Energy recovery linacs would also provide the beams for the linac-ring option of high-luminosity electron-hadron colliders. The investigation of beam-beam effects, a major obstacle limiting luminosity and beam lifetime in colliders, requires sophisticated simulations that include three-dimensional effects and machine nonlinearities.

Access to the spin degrees of freedom is essential for unraveling the underlying forces between colliding particles. These experiments require high-brightness intense polarized electron, proton and light-ion sources.

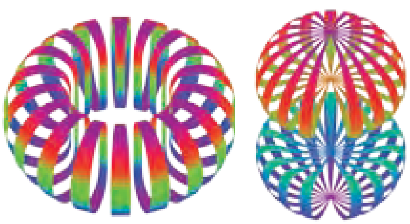
Targets and stripper systems that can withstand megawatt-levels of beam power are key for producing rare isotope beams, generating intense neutron fluxes and beams of kaons, muons and neutrinos. Technical challenges include thermal management, radiation and thermal shock of solid or liquid materials.

FINDINGS

The most promising R&D avenues involve development, by one or more orders of magnitude, of energy-efficient high-power accelerators, polarized and unpolarized high-intensity sources of electrons, protons and ions, and cooling and other technologies for achieving high luminosity.

R&D on high-intensity low-loss ion accelerators for the efficient production of radioisotopes is essential not only to open up new research frontiers in nuclear physics but also for applications in medicine, industry and national security.

R&D on intense polarized electron and light-ion sources, on high-energy cooling of hadron beams, and on high-current, efficient, multi-pass energy recovery linacs are of critical importance for the advancement of hadron and lepton-hadron colliders.



Computer simulations of the deuteron, investigated in precision experiments at Thomas Jefferson National Accelerator Facility *Images courtesy of S. Pieper, Argonne National Laboratory*

Computer image of a particle collision at the PHENIX detector at Brookhaven National Laboratory's Relativistic Heavy Ion Collider *Image courtesy of Relativistic Heavy Ion Collider*

Particle Physics

Particle physics, also called high-energy physics, asks basic questions about the universe. Over the past 50 years, with particle accelerators as their primary scientific tools, particle physicists have achieved a profound understanding of the fundamental particles and physical laws that govern matter, energy, space and time. The theoretical and experimental breakthroughs that have produced this Standard Model of particles and forces are among the triumphs of 20th century science. Recent discoveries have shown, however, that this elegant view of the universe must be incorporated into a still deeper theory. Current and future particle physics experiments around the world provide the capability to address a set of well-defined questions that, together, define the path for particle physics in the 21st century.

NEEDS, OPPORTUNITIES AND TECHNOLOGIES

The High Energy Physics Advisory Panel identified three frontiers of scientific opportunity for the field: the Energy, Intensity and Cosmic Frontiers. Answers to questions about the fundamental physics of the universe will come from combining the most powerful and insightful observations at each of the three frontiers. At two of them, the Energy and Intensity Frontiers, particle accelerators will be the essential scientific tools for exploration, defining the potential for discovery.

At the Energy Frontier, using high-energy colliders, physicists discover new particles and directly probe the architecture of the fundamental forces at ever-smaller scales. At the Intensity Frontier, using intense beams, experiments illuminate the nature of neutrinos and observe rare processes that can reveal new physics at very high energies. Research at both frontiers informs us in complementary ways about the origin and evolution of the early universe.

Accelerators using leptons, such as electrons and positrons, and hadrons, including protons and antiprotons, have played complementary roles in particle physics discoveries, and both will have essential roles in the future. Experimenters use hadron accelerators for a wide-ranging search for new phenomena and lepton colliders as precision probes of these new phenomena. Designing and building the accelerators of the future will require not only refinement of existing technologies but breakthroughs that lead to fundamentally new concepts.

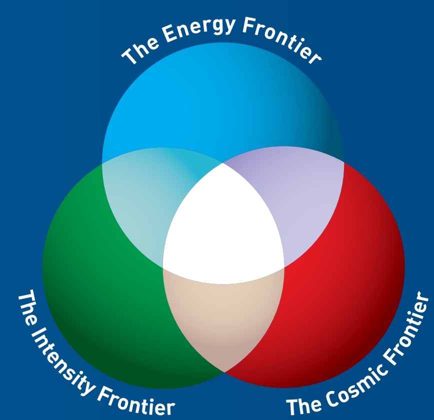
TECHNICAL CHALLENGES

Particle physics research at the energy and intensity frontiers will require R&D in key areas of accelerator technology. Attaining higher energies will require higher electric field gradients, reaching 100 million volts per meter and above. Advances in superconducting radio-frequency acceleration at higher critical temperatures seem possible with new materials and manufacturing techniques. The challenge will be to make these materials pure enough and with sufficiently perfect surfaces to support high-gradient beams. Radio-frequency (RF) generation by deceleration of intense beams could yield lower-cost multi-TeV room-temperature linacs. Whether such beams can be generated and compressed and achieve gradients above 100 megavolts per meter requires demonstration, which will depend on advances in understanding RF breakdown, developing new acceleration structures, and achieving cost-effective high-power RF.

Laser- and beam-driven plasmas, and to a lesser extent dielectric loaded structures, have achieved gradients a thousandfold greater than those of conventional accelerators. To develop practical accelerators with this approach will require demonstrations with large bunch charges and successive accelerating segments, as well as advances in efficient high-power laser sources.

Higher-energy colliders require magnets with higher critical fields than are now achievable. Ongoing research on new cables needs continued support.

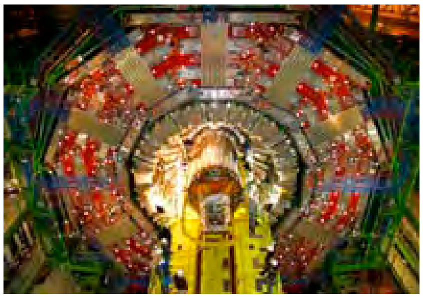
Particle physics discoveries at the Energy and Intensity Frontiers depend on advancement in accelerator science and technology.



High-critical-temperature, or HTc, superconducting materials offer magnetic fields above 12 Tesla, operating temperatures over 50K, and decreased sensitivity to operating temperature. The R&D challenges include material properties, total current-carrying capabilities, and cost. Continued support of this work is of very high priority.

Muons, unlike electrons, bend in a magnetic field without significant energy loss to synchrotron radiation. Multiple-pass acceleration in magnetic rings could pave the way for compact muon facilities and efficient use of accelerating structures. Recycling linacs or fixed-field accelerating gradient rings are also possible. Outstanding issues for muon colliders include accommodating the large beam sizes and addressing radiation from muon decay.

Megawatt proton beams will drive next-generation high-intensity accelerators. Intensity-frontier beams need R&D on targets, beam injection, beam manipulation in storage rings, and radiation-hard materials. Understanding beam loss is critical for achieving future high-power accelerators. Beam halo simulations to support new designs need to be checked experimentally on currently operating accelerators.



The CMS detector at CERN's Large Hadron Collider *Photo: Michael Hoch, Adventure Art*

Compact and well focused beams are critical for colliders, requiring new cooling mechanisms and precision beam handling. Muon accelerators will require the development of a new rapid-ionization cooling technique with high-field, high-temperature superconducting solenoids, high-gradient radio-frequency cavities operating in magnetic fields, and high-field dipole magnets that can work in a high density of electrons from muon decay. Stochastic cooling systems based on very high-frequency techniques (~100GHz) have potentially very short cooling times suitable for generating ultra-low-emittance hadron beams.

The high luminosities needed for future electron-positron colliders require improvements in high-intensity positron production. Beam quality preservation will require R&D on achieving low-impedance, ultra-high-vacuum pipes and precise alignment of focusing magnets at the micron or even submicron level. The problem is exacerbated in plasma channel accelerators with their strong transverse fields.

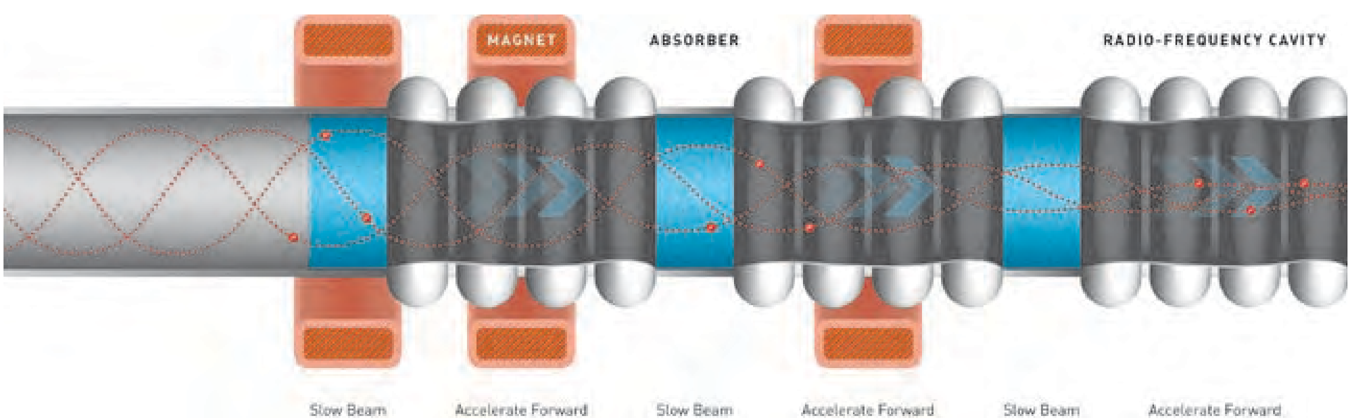
FINDINGS

High-magnetic-field magnets lead to more compact circular accelerators and higher-energy collisions. They will also enable effective focusing systems for high-intensity applications. High-temperature superconducting magnets have significant potential to advance magnet technology.

Larger accelerating gradients would make possible more compact and cost-effective accelerators. Promising avenues include higher-field superconducting cavities, RF generation by intense drive beams, and accelerating fields from plasma-driven wakefields.

New techniques using ionization cooling and very high-frequency stochastic cooling show promise as methods to control beams for high-intensity collisions.

Concept for generating high-quality muon beams for a future energy-frontier accelerator *Image: Sandbox Studio*



Accelerators for X-ray and Photon Science

Over the last four decades, light sources—accelerators producing photons from the infra-red to hard x-rays—and the sciences that use them have made dramatic advances that cut across many fields of research. Brightness has increased a thousandfold every decade. This remarkable progress has opened up new scientific opportunities, to the point where there are now about 10,000 scientists in the U.S. using x-ray beams for research in physics and chemistry, biology and medicine, earth sciences, and many more aspects of materials science and development.

Light sources based on dedicated electron storage rings have achieved x-rays with subatomic-scale wavelengths with excellent beam stability. They produce precision beams smaller than a micron in diameter for exploring properties of fine-grained complex materials and allow high-pressure and high-temperature studies with significant impact for materials research and geosciences. Technical advances have made high-resolution imaging an important tool in medicine, biology, materials and environmental science. Other techniques using x-rays in studies of liquids, as well as bulk and interface properties of advanced materials, have also blossomed to allow *in situ* probing of physiochemical processes.

Linear accelerators with free electron lasers for x-rays, or XFELs, use the principle of self-amplified spontaneous emission, or SASE, to produce extremely intense, ultra-short pulses of coherent x-rays. In flashes that last less than 100 femtoseconds, XFELs provide as many photons as storage rings currently produce per second, and gains in peak brightness from these sources reach ten orders of magnitude. Research areas include the study of the structure and dynamics of nonperiodic macromolecular complexes; investigation of nanoscale dynamics and collective behavior in condensed matter; and explorations of femtosecond chemistry to study the building and breaking of chemical bonds in photosynthesis and in materials under extreme conditions.

Aerial view of the Advanced Photon Source at Argonne National Laboratory
Photo courtesy of Argonne National Laboratory

NEEDS, OPPORTUNITIES AND TECHNOLOGIES

Most research in x-ray-based science has investigated material systems in equilibrium, using static methods of observation. However, many of the most scientifically significant processes take place during transition from one state of matter to another, far from equilibrium. Extreme length and time scales characterize the behavior and complexity of matter. Basic physics principles overlap chemistry, biology, geosciences, medicine, and broad fields of engineering science. What are the principles that govern far-from-equilibrium behavior? How does the complexity of matter develop in time and space? What are the principles of pattern formation, development and self-organization in nature? Such questions will lay the foundation for understanding the far-from-equilibrium processes that determine the functions of materials around us. Moving from passive observation to active control requires a new generation of light sources with the highest brightness and with specialized properties that include laser-like coherence of the x-rays from XFELs.

The time evolution of systems, whether excited by a single photon of sunlight in photosynthesis or by a dynamic, high-pressure shock wave in inertial confinement fusion, represents new areas for the investigation of the behavior of matter far from equilibrium. Researchers would probe not only the dynamics of electrons, spins and phonons but also structures at the atomic and molecular level, and the nanoscopic, mesoscopic orders, and continuum scales.

Central to these scientific challenges is the ability to image, understand and control matter as a function of energy, momentum, space, and time. Materials often drive progress in technology. Recently, materials in the form of nanostructures and complex materials, whose properties arise from electron correlations rather than from independent electrons, have become increasingly important.

There are now about 10,000 scientists in the U.S. using photon and x-ray beams for research in physics and chemistry, biology and medicine, earth sciences, and many more aspects of materials science and development.

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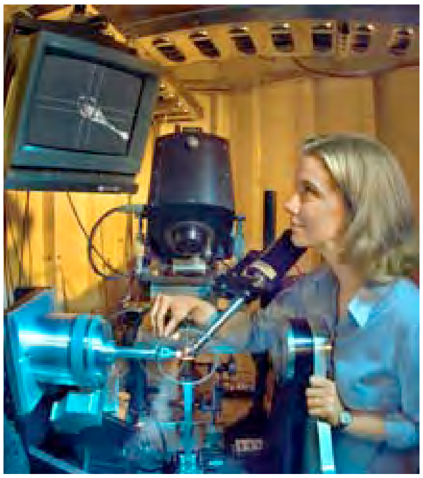
The imaging properties of XFELs will revolutionize our ability to see, and thus manipulate, matter on the atomic scale.

An example of technological progress using XFELs could include extensions of precision frequency standards from the optical region to x-ray frequencies allowing ultrahigh-resolution metrology. As a result, researchers could gain insight into the measurement of time variation of the fundamental constants of nature, symmetry postulates, graininess of space and gravitational red-shift.



Researcher at the crystallography beamline of Lawrence Berkeley National Laboratory's Advanced Light Source *Photo: Roy Kaltschmidt, Berkeley National Laboratory*

TECHNICAL CHALLENGES

The future of x-ray science depends on improving existing light sources and developing the light sources of tomorrow. Challenges to improving present light sources will call for significant R&D.

Future light sources will be characterized by orders-of-magnitude improvement in key capabilities including radiation coherence with control of the quality of temporal structure and energy bandwidth of pulses; spectrum coverage with wavelength range from sub-millimeter (terahertz radiation) to sub-atomic (hard x-rays); and photon power, including pulse energy and repetition rate. The potential architectures for these light sources include free electron lasers, energy recovery linacs, so-called ultimate storage rings, and laser-driven sources.

Seeded free electron lasers offer fully controlled temporal coherence and intrinsic time stamping of the radiation, in addition to the transverse coherence possible with self-amplified spontaneous emission x-ray FELs. Operating in the SASE low-charge mode, FEL amplifiers have the potential to approach wavelengths near quantum-limited performance. FEL oscillators will also offer controlled temporal and bandwidth properties.

Energy recovery linacs offer flexible timing structure and high average brightness. These transformational sources will have performance superior to that of existing storage rings and linac-quality beam at very high (GHz) repetition rates. Long-term plans might also combine FELs with energy recovery linacs.

Storage rings are currently the workhorses of x-ray experiments. Storage ring technology has the potential to achieve nearly full transverse coherence in the soft and hard x-ray range up to 10 keV. Storage rings also offer stability, high power, and accommodation of large numbers of users.

Areas of cross-cutting R&D with the most promise for transformative innovations are photo cathodes and injectors optimized for brightness and lifetime; high-power optical lasers for beam control and seeding, driving photo cathodes and pump-probe experiments; techniques for laser manipulation of beams and seeding the FEL process; continuous-wave superconducting radiofrequency accelerating structures; and synchronization and timing technology to the sub-femtosecond level over kilometer distances; as well as advanced detector technology.

As with other applications of accelerators, R&D on sources for x-ray science sources rests on increasingly large-scale end-to-end simulation capabilities. Reducing the cost of future light sources to meet growing user demands will also require significant R&D.

The future of x-ray science depends on improving existing light sources and developing the light sources of tomorrow.

FINDINGS

Integrating advances in component technologies, especially in free electron lasers and energy recovery linacs, will require prototype test-bed facilities. Such test facilities serve multiple accelerator R&D purposes and support advanced accelerator education and training.

Advances in optical and near infrared laser technology will create opportunities for x-ray science. High-power lasers will make possible unique x-ray sources. They are useful as seed lasers and are essential for laser plasma acceleration and photocathode injectors. The advanced optics R&D that multiple vendors outside the U.S. are now pursuing addresses these needs.

Neutron Science

Neutron scattering offers a unique probe of the structure and dynamics of materials. Researchers use large facilities for research on condensed matter physics, applied engineering materials, materials chemistry, geoscience, soft matter such as polymers and micelles, and biological materials. The diverse applications of neutrons require optimized and highly specialized instruments to serve the particular needs of different user communities.

The use of neutron scattering as a research tool began in the late 1940s and early 1950s with nuclear reactors as sources of neutrons. In the 1960s, researchers raised the possibility of using accelerator-produced neutrons. A continuous accelerator-based neutron source began operating in Switzerland about a decade ago. In the meantime, intense pulsed neutron sources had begun operating in the late 1970s and early 1980s. They eventually achieved significant peak flux, making possible new classes of innovative experiments. This work had enormous impact on materials research, and paved the way for the state-of-the-art and currently the world's most intense Spallation Neutron Source, or SNS, at DOE's Oak Ridge National Laboratory, operating at power levels of 1 megawatt.

Major successes of accelerator-based neutron sources include determining the crystal structure of high-temperature superconductors; the observation of magnetic quantum fluctuations in single-crystal materials including antiferromagnetic chains, colossal magneto-resistance systems and high-temperature superconductors; elucidating the structures of ionic liquids; and detailed characterization of polymer films and interfaces. Emerging research areas include extreme environments such as high pressure, *in situ* studies of engineering and energy-related materials, and biological applications of neutron scattering.

NEEDS, OPPORTUNITIES AND TECHNOLOGIES

Increasing the flux of useful neutrons is crucial for enhancing the capabilities of accelerator-produced neutrons for materials research. The greatest need is for a high flux of thermal or cold neutrons. Since the neutrons produced by the beam hitting the spallation targets generally have very high energy, producing the low-energy, end-use neutron spectrum requires moderation of the spallation-produced neutrons.

Developing the next generation of sources requires a focus on reliable accelerators with increased power, spallation targets, moderators and optimized end-user instruments. To develop classes of experiments that are now impossible will require consideration of new types of sources, including long-pulsed spallation sources and perhaps even high-power continuous spallation sources. Both could be based on high-power linacs from 5-20 megawatts, with energies of 1-3 GeV. Reliable and uninterrupted operations are a key requirement of end users.

Increasing the flux of useful neutrons is crucial for enhancing the capabilities of accelerator-produced neutrons for materials research.

View into the linac portion of the Spallation Neutron Source at Oak Ridge National Laboratory ***Photo courtesy of Oak Ridge National Laboratory***

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Cost is currently a barrier to transformative advances, calling for developments that improve robustness and reduce operating costs.

TECHNICAL CHALLENGES

Cost is currently a barrier to transformative advances, calling for developments that improve robustness and reduce operating costs. Progress requires understanding the failure rates of components and addressing problems related to beam halo and beam loss.

R&D priorities include long-pulsed sources, with maximum power in pulses of ~2-4 ms and energies of ~1-3 GeV for spallation sources at repetition rates of 10-30 Hz. These will probably be linac based, and similar high-power linac-based continuous sources also warrant consideration. A second priority is short pulses (100 ns–1 μs) with maximum energy per pulse of hundreds of kilojoules, energies of ~1 or more GeV for spallation at repetition rates of 30–60 Hz. The development and deployment at universities and small centers of inexpensive and efficient sources based on low-energy accelerators (13-20 MeV) for neutron production from scattering reactions with variable pulse lengths and frequencies for R&D is a third priority.

FINDINGS

Controlling beam loss and instabilities in accelerators for neutron science will require improved methods, including understanding beam-loss mechanisms and improving beam control. This effort will include developing advanced beam diagnostics and analysis methods, reliable computer models with proper verification tools, and progress in theoretical understanding. Overcoming detrimental beam-instability issues will call for developing novel methods of beam-distribution control and advanced feedback.

Future neutron sources will require investment in the development of appropriate targets and moderator systems suitable for high-power spallation sources.

There is a need for technologies for radio-frequency power sources, superconducting cavities and ion sources, as well as improved technologies to enhance beam reliability, including injection. Reliable and predictable operations will have a huge impact on scientific capabilities.

Five national laboratories collaborated to build the Spallation Neutron Source at Oak Ridge National Laboratory. *Photo courtesy of Oak Ridge National Laboratory*

DISCOVERY SCIENCE GENERAL FINDINGS

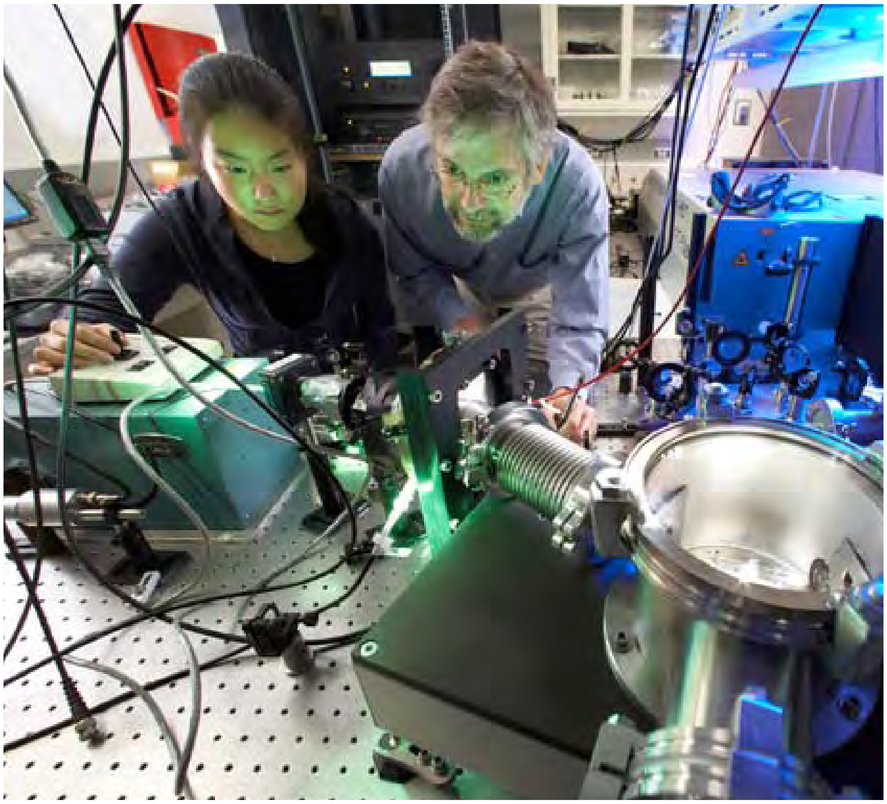
Every field of accelerator-based science has particular challenges and opportunities for maintaining leadership in accelerator science, technology and workforce development. However, some key observations apply across the board.

Accelerators have found ever-expanding uses in discovery science, medicine, security, energy and the environment, and industry. However, continued development to maintain and strengthen the nation's competitive position in the global enterprise of accelerator technology will require a new level of coordination among government agencies. National and international R&D consortia that bring diverse physical and intellectual resources to bear on national and international programs have proven their value and should be expanded. Mechanisms must be found and developed to encourage these collaborations.

The use of operating accelerators and of special dedicated accelerator test facilities for beam science and technology development are an essential component of a frontier accelerator program and need to be strongly supported.

Further advances in accelerator technology depend on recognizing and encouraging the science of accelerators as a field of science in its own right. Attracting the caliber of scientific minds essential for progress in this field requires a vibrant program of accelerator science research that will yield advances in accelerators for America's future.

Continued development to strengthen the nation's competitive position in the global enterprise of accelerator technology will require a new level of coordination among government agencies.



Stanford University graduate student Jahee Kim and Phil Bucksbaum, director of the Photon Ultrafast Laser Science and Engineering Center at SLAC National Accelerator Center
Photo courtesy of SLAC

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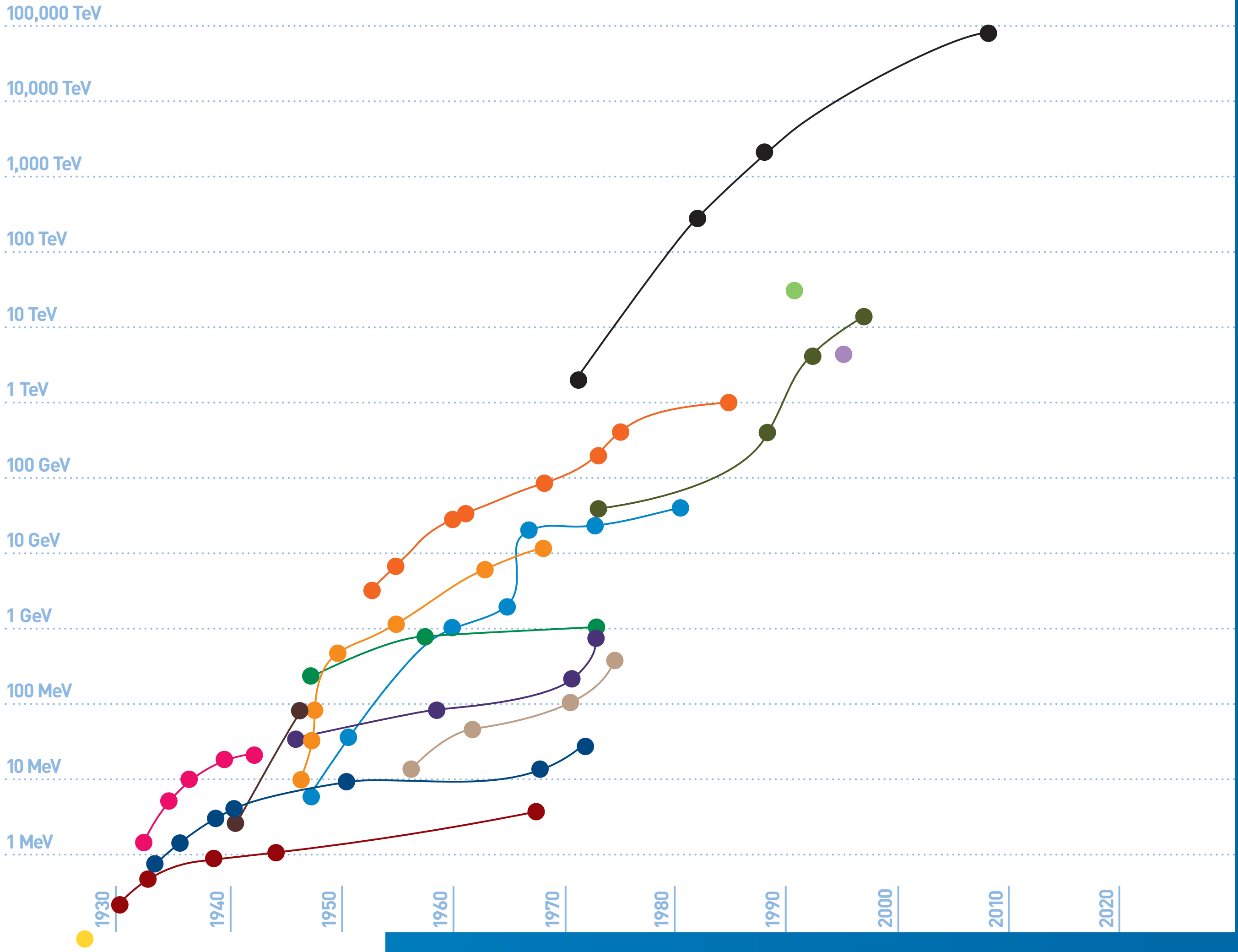
Livingston Plot



Energy reach of the highest-energy particle accelerators ever built. The energy of particle colliders is plotted in terms of the energy that the particles would need if colliding with a proton at rest. Using these units, the energy of at the Large Hadron Collider corresponds to the energy of nearly 100,000 TeV. *Image adapted from the 2001 Snowmass Accelerator R&D Report Text: Adapted from* symmetry *magazine, October 2009.*

Physicists have been inventing new types of accelerators to propel charged particles to higher and higher energies for more than 80 years. Today more than 30,000 accelerators are in operation around the world—in industry, in hospitals, and at research institutions.

Accelerator expert M. Stanley Livingston summarized world-wide advances in high-energy accelerators in a book published in 1954. An illustration in his book—the latest update is displayed on this page—has become a hallmark in the field of accelerator physics. Livingston noted at the time that advances in accelerator technology increase the energy records achieved by new machines by a factor of 10 every six years.

First accelerator

Most accelerators in operation today, including thousands of machines used for treating the surfaces of materials, rely on the same principle of resonance acceleration that Norwegian engineer Rolf Wideröe explored when he built the world's first accelerator in Aachen, Germany in 1928. His linear accelerator, powered by an alternating voltage, propelled potassium ions through an 88-cm-long glass tube, achieving an energy gain equivalent to twice the peak voltage he used. This proof of principle opened the door to a vast new field of research and many types of accelerators.

Cyclotrons

More than 350 cyclotrons around the world produce radioactive isotopes for medical applications, such as PET scans. Inspired by Wideröe's success, Ernest Lawrence and his student M. Stanley Livingston built the first of these circular accelerators, about four inches in diameter, and operated it in 1931 in Berkeley. The cyclotron's magnetic field forces particles to travel in spirals. On each turn, the particles cross an electric field that accelerates them to higher energy.

Cockcroft-Walton electrostatic accelerators

In 1932, John Cockcroft and Ernest Walton became the first scientists to split the atomic nucleus with artificially accelerated particles when they aimed a proton beam at lithium atoms. Physicists still use Cockcroft-Walton accelerators to deliver strong, steady streams of low-energy protons. The machines can turn alternating currents into electrostatic fields corresponding to more than one million volts.

Van de Graaff electrostatic accelerators

Scientists used this type of accelerator for several decades in physics and biomedical research. Commercial companies now build modern versions of this machine for the same purposes. Invented at Princeton University in the 1930s, the accelerator generates a high voltage by charging a large sphere with a moving belt. At the Museum of Science in Boston, visitors can see a Van de Graaff machine in action.

Betatrons

In 1940, Donald Kerst at the University of Illinois modified the design of the cyclotron to accelerate particles to higher energy. The betatron's large magnet provides a variable field and keeps particles on a circular orbit inside a beam pipe, a major step forward in accelerator technology. In 1957, Dr. O. Arthur Stiennon opened in Wisconsin the first private medical center to treat cancer patients with a betatron.

Synchrocyclotrons

For many years physicists struggled to build accelerators that work for both low- and high-speed particles: slow particles gain both energy and speed when traveling through an electric field while particles traveling close to the speed of light gain energy but almost no speed. This creates a timing problem in accelerators. The synchrocyclotron, invented in the 1940s, solved the problem by introducing an electric field with variable frequency, paving the way for better accelerators.

Linear accelerators

Physicists built the first modern linear accelerators after World War II, using microwave technology developed for radar. Today, thousands of hospitals use linacs for radiotherapy in cancer treatment. Luis Alvarez built the first standing-wave linac to accelerate protons at UC Berkeley in 1946. A team at Stanford University constructed the first traveling-wave linac to accelerate electrons in 1947. Today, scientists often use linacs to give heavy particles an initial boost before injecting them into the circular machines that accelerate them to high energy.

Electron synchrotrons

The operation of the first electron synchrotron in the United States, at General Electric in 1946, led to the discovery of synchrotron radiation, the light emitted by charged, high-energy particles traveling in a circle. Today, more than 50 electron synchrotrons, known as light sources, produce intense beams of light for research in material science, chemistry, molecular biology, and other fields. In a synchrotron, the particles stay on a fixed circular path and the beams can circulate for long periods of time.

Proton synchrotrons

The discovery in the 1950s of strong beam focusing, which controls the size of a particle beam through a series of magnets, allowed the construction of large, circular proton accelerators for nuclear and high-energy research, starting at Brookhaven National Laboratory and the European laboratory CERN. Hospitals have begun to use proton synchrotrons for cancer treatment.

Storage ring colliders

Storage ring colliders circulate two beams of particles in opposite directions and smash the particles into each other. They have led to the discovery of many of the subatomic forces and building blocks of matter. Today, machines at KEK, CERN, Fermilab, and Brookhaven make electrons, positrons, protons, antiprotons, and ions collide. Scientists also are pursuing a new type of machine that would smash muons into each other.

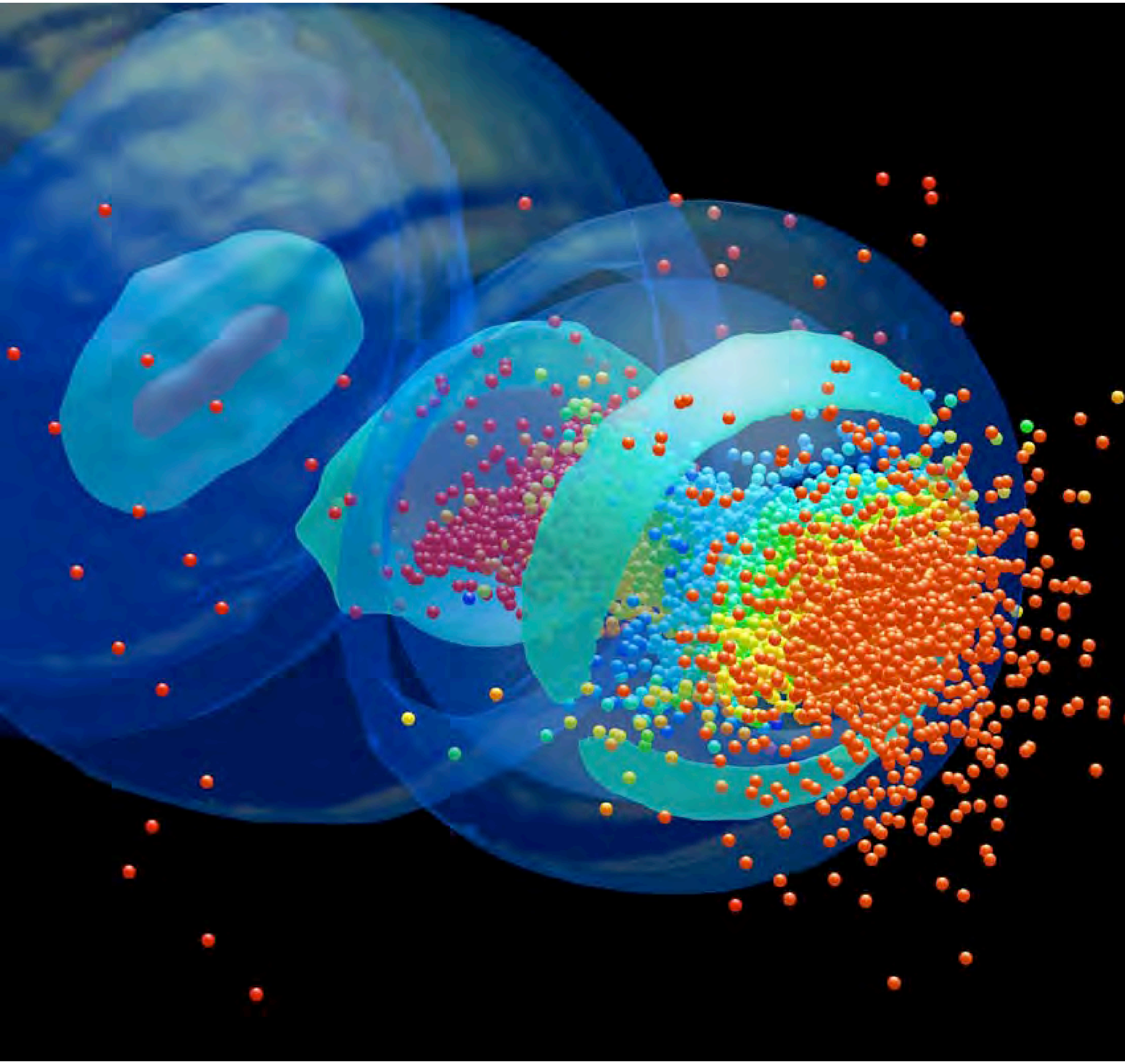
Linear colliders

The Stanford Linear Accelerator Center started operating the world's first linear particle collider in 1989 using conventional radio-frequency cavities operating at room temperature. Today, scientists are developing superconducting RF cavities that could power future linear colliders, accelerating electrons and positrons to much higher energy than achieved at SLAC.

Accelerator Science and Education

Accelerator science, the basic science of beams of particles, investigates and characterizes their production and manipulation and their interactions with electromagnetic fields, plasmas or matter. Accelerator science has advanced dramatically in the decades since accelerators first emerged as powerful tools across the breadth of the experimental sciences. Accelerator science will lead the way to future accelerators for virtually every branch of science and for a broad spectrum of applications to meet national needs.

Simulation of the E-167 Plasma Wakefield Acceleration Experiment at SLAC National Accelerator Center. In the experiment, 42 GeV electrons from the SLAC linac doubled their energy in less than one meter. The surfaces are regions of constant plasma density, while the spheres represent the beam electrons. *Image: C.K. Huang (Los Alamos National Lab) and Miaomiao Zhou (UCLA) with visualizations created by F. S. Tsung (UCLA)*



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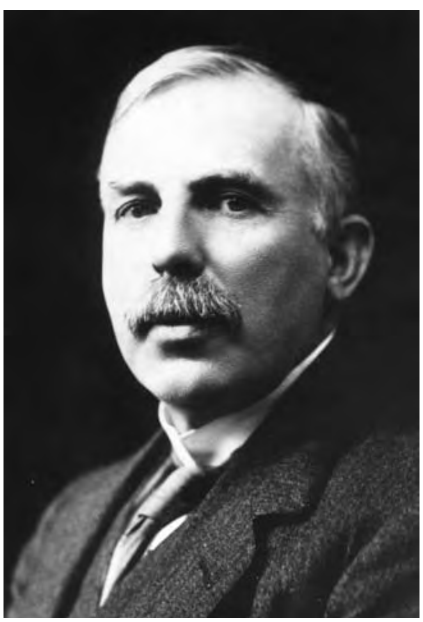
Accelerator science will lead the way to future accelerators for virtually every branch of science and for a broad spectrum of applications to meet national needs.



Ernest Lord Rutherford ***Photo courtesy of Cambridge University Library, courtesy AIP Emilio Segre Visual Archives, Rutherford Collection***

The history of accelerators has shown over and over again that innovation and careful R&D, often accompanied by unexpected developments, can overcome seemingly insurmountable barriers to progress. In the 80 years since their invention, accelerators have increased beam energies one hundred million times, beam intensities by a factor of one million, and beam brightness—a measure of geometric, temporal and spectral sharpness—by more than ten orders of magnitude.

We can expect major, perhaps even revolutionary, further advances. The accelerating field is a good example. Ernest Lord Rutherford, the discoverer of the atomic nucleus, suggested in the late 1920s that it should be possible to generate an accelerating field of about ten million volts over an accelerating distance that fits into a large room. He could not have anticipated that now radio-frequency accelerators provide tens of millions of accelerating volts over distances of less than one meter. Yet today, to stay with this example, we are discussing future accelerating schemes, particles riding on plasma wakefields, that might increase acceleration by a factor of a thousand. Or that might, conversely, provide tens of millions of accelerating volts over distances unimaginably small: a few hundred microns. This latter vision, stimulated by promising results of initial R&D, will require substantial research effort before becoming everyday reality. It is one of the many areas of R&D that hold great promise for the future of accelerator science and technology.

NEEDS, OPPORTUNITIES AND TECHNOLOGIES

Ultrahigh-gradient acceleration concepts are an important area of accelerator science research, because high-gradient techniques have great transformational potential for many accelerator applications. Particle physics has long supported aggressive research to extend the reach of existing accelerating technologies and to pioneer new concepts. The capability of high-temperature radio-frequency structures has extended their reach well past 100 MeV/m. New methods are under development using direct laser acceleration (1 GeV/m), beam-driven dielectric wakefield acceleration (few GeV/m), and ultrahigh-gradient laser- and electron-beam-driven plasma wakefield accelerators (>10 GeV/m). They offer the promise of more compact light sources in the near term and higher-energy colliders in the longer term.

The development of ultra-high-gradient compact accelerators with high beam quality would lead to radiation sources covering the entire electromagnetic radiation spectrum from coherent terahertz to high-energy gamma rays and offer unique high peak-brightness capabilities. Universities and small research laboratories might build free-electron lasers operating in the soft x-ray regime. For low-repetition-rate light sources (1-10 Hz) operating at 1-10 GeV, researchers may deploy compact laser-driven plasma wakefield accelerators in the next five to ten years.

Users of future light sources seek temporal and spectral control at scales well beyond those currently achievable. The research that supports the development of attosecond-class acceleration techniques, such as direct laser and high-density plasma acceleration, may enable control of beam properties on a time and spectral scale that is orders of magnitude finer than presently available, with great benefit to the next generation of ultra-fast light sources.

For medical and security applications, compact monochromatic x-ray and gamma-ray sources based on Thomson scattering of laser light off a high-quality electron beam could lead to high-resolution imaging. Laser-based proton and ion accelerators for particle therapy are emerging as a possibility. Laser-solid target interaction has produced proton and ion beams with energies in the tens of MeV per nucleon, with emittance one to two orders of magnitude below conventional sources. Techniques for obtaining higher-energy beams (100s of MeV) with low energy spread are in development.

Besides high-gradient research, urgent accelerator science topics include six-dimensional beam cooling for muon beams, manipulation of polarized beams, ultimate electron storage rings that produce diffraction-limited emittance, energy recovery linacs, optical stochastic cooling techniques, microbunch seeding of high peak-current electron beams, and coherent electron cooling of beams.

Accelerator science needs a strong theoretical foundation, with advances in accelerator R&D intimately coupled to strong efforts in accelerator theory. A theoretical understanding of the experimental observations is critical to point the way toward innovative concepts and transformational technologies, making support of accelerator theory an essential part of accelerator R&D.

Often a new theory plays the fundamental role leading to innovative concepts and transformational technologies, making support of accelerator theory an essential part of accelerator R&D.

Researchers at Lawrence Berkeley National Laboratory's TREX laser, used in a series of experiments that accelerated electrons from zero to one billion electron volts in three centimeters ***Photo: Lawrence Berkeley Laboratory***

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World-class facilities for experiment, theory and simulation, and for educating accelerator scientists, are the key to developing the accelerator science that will form the foundation of future accelerator innovation to address 21st-century challenges.

TECHNICAL CHALLENGES

The next challenge in ultrahigh-gradient techniques for high-energy physics is to demonstrate the production of relevant energies and, ultimately, beam power for collider applications. The demonstration of high-quality electron beams from single plasma-based modules and experiments aimed at demonstrating the capability of staging modules reliably to achieve beam energies useful for particle physics have also begun.

Beyond these important experiments, high-power applications in both particle physics and basic energy sciences require demonstration at high average powers (i.e. gradient and repetition rate). In addition, future light source applications need development of high-quality femtosecond and attosecond beams.

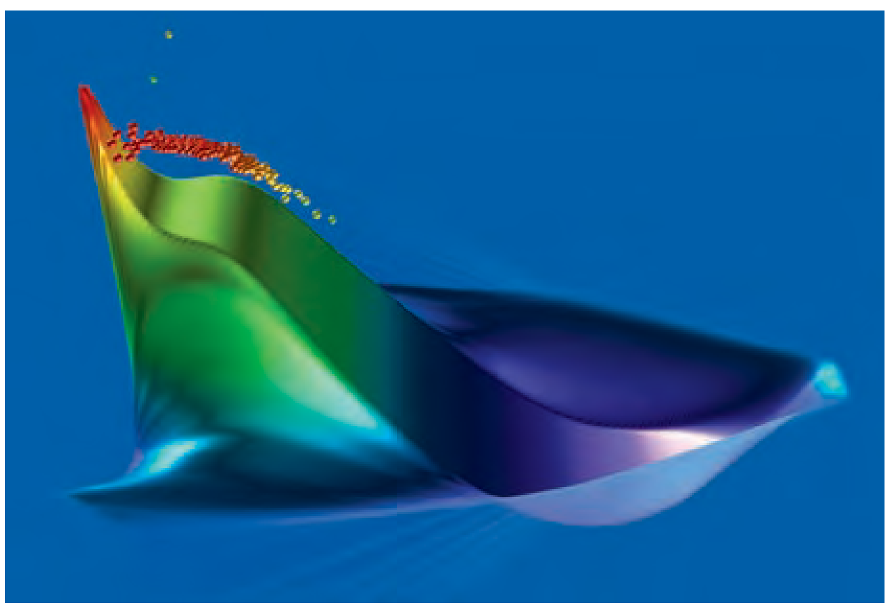
Accelerator science will benefit from significant investment in developing economical high-power radio-frequency sources and efficient high-average-power laser sources suitable for driving accelerators. Crosscutting research will be essential for the development of metals, dielectrics and plasmas for structure-based accelerators powered by microwaves, beams and lasers.

FINDINGS

World-class facilities for experiment, theory and simulation, and for educating accelerator scientists, are the key to developing the accelerator science that will form the foundation of all future accelerator innovation to address 21st-century challenges. Building and operating such facilities will require sustained investment over the next few decades.

Overcoming impediments to successful accelerator innovation in ultra-high gradient accelerator techniques will require comprehensive R&D and the concerted engagement of the national laboratories, universities and industry, supported by dedicated funding.

Research in accelerator theory and simulation should receive strong support as an essential element of accelerator science.



In this simulation of a plasma accelerator, a laser or electron beam (not shown) shoots through the plasma from left to right, shaping electrons in the plasma into a large wave. Surfing the crest of this wave, a bunch of electrons accelerate to high energies in a very short distance.
Image: C. Huang, Los Alamos National Laboratory

ACCELERATOR SCIENCE EDUCATION

More than any other factor, the education of the next generation of accelerator scientists and engineers will determine the future of accelerator-based science and technology in the United States. Tomorrow's accelerators will be extraordinarily challenging to design, build and operate. They will need the sustained efforts of many outstanding and highly trained scientists and engineers. Yet only a handful of U.S. universities offer formal training in accelerator science and technology. Many engineering departments no longer offer courses in technologies, such as power electronics and microwave and radiofrequency systems, that are crucial to accelerators. Further, despite a record of high-impact publications and award-winning dissertations, accelerator physics is often regarded as limited in science content, discouraging the development of accelerator physics faculty and the training of graduate students.

At U.S. national laboratories and accelerator-associated universities, currently about half the accelerator scientists were born abroad, and many received their highest degrees from foreign universities. As the opportunities for accelerator scientists in other countries grow, our own nation will lose that source of intellectual power and technological skill, exacerbating the already acute need for more and better accelerator education here at home.

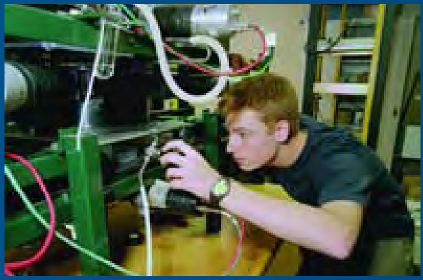
Strengthening the role of universities in accelerator R&D is essential. The few universities with research or test accelerators that support faculty lines provide the tightest link to accelerator-science education. These universities emphasize innovation in accelerator science and offer opportunities in accelerator science and technology to undergraduate physicists and engineers. An expanded accelerator-physics and engineering faculty at more universities, and strong university-based research programs to support these faculty lines, would go far toward attracting bright young minds to accelerator science and engineering.

Collaboration between national laboratories and research universities is a natural approach to attract, train and educate a new generation of accelerator scientists and engineers. Since 1982 the U.S. Particle Accelerator School has exemplified such a successful partnership, offering rigorous graduate and undergraduate courses in accelerator science and engineering. University–laboratory centers for accelerator research and education offer another avenue and need nurturing and expanding. They provide invaluable access to accelerator facilities for training and thesis research.

FINDING

Continued U.S. innovation in basic accelerator R&D rests on the next generation of accelerator scientists. The nation must make continued long-range investments to create opportunities for education and training, an effort that requires advanced operating accelerator facilities at national laboratories and increased support for university programs in accelerator science. It is critical to maintain and strengthen national laboratory-university partnerships and to support schools for accelerator science and technology education.

Only a handful of U.S. universities offer formal training in accelerator science and technology.



More than any other factor, the education of the next generation of accelerator scientists and engineers will determine the future of accelerator-based science and technology in the United States. ***From top: photos courtesy of CERN, Fermilab Visual Media Services, W.A. Barletta***

Technical, Program and Policy Directions

Five working groups of accelerator experts, reporting from DOE's Office of High Energy Physics-sponsored workshop on *Accelerators for America's Future*, individually defined their stakeholders; enumerated challenges to accelerator advancement; identified promising, transformative accelerator research and development; and offered guidance to strengthen the connection between basic accelerator research and technology deployment. The groups identified the most compelling future opportunities and made suggestions for improving accelerator research and development. Analysis of the working groups' reports and findings readily reveals a number of common directions for technological progress and policy initiatives. Taken together, these common technical and policy themes offer the opportunity and the framework to coherently and strategically promote accelerator research and development across a comprehensive set of applications to meet pressing national needs.

ACCELERATOR OPPORTUNITIES

Each working group identified several opportunities for accelerator-based applications with transformative potential. Accelerator-driven systems for power generation and the transmutation of nuclear waste, as well as for the treatment of flue gases and waste and drinking water, could address significant national energy and environmental challenges. In medicine, isotope generation and charged-ion cancer therapy offer promising applications of accelerator technology. Industrial opportunities involve replacing inefficient, environmentally harmful thermal processes with energy-efficient and "green" electron-beam or x-ray processes and replacing industrial radioactive sources with accelerators. For national security and defense, new rugged, compact, turn-key accelerators will lead to high-impact applications in defense, cargo interrogation, and monitoring. Discovery science would profit from higher-energy colliders, muon colliders, laser- and electron-beam-driven plasma wakefield accelerators, and more intense light sources using advanced free electron lasers and energy recovery linacs.

TECHNICAL DIRECTIONS

Realizing the opportunities identified by the working groups to apply accelerator technologies to meet national challenges will require coordinated, sustained progress in a number of technical areas. Not surprisingly, the individual groups identified many overlapping areas for research and development. Reduced accelerator size and cost, along with improved accelerator reliability and efficiency, were among the general technical characteristics most often cited. More specific technical improvements reported were higher-current particle sources and beams, higher-power radiofrequency sources, improved beam control and simulation, and increased field strengths in superconducting accelerator cavities and magnets.

To achieve economic and operational viability, accelerator performance for energy and environmental applications will require significant technical progress. Reliability, for example, will need to far exceed levels typically found in physics research facilities, reaching beyond 99 percent duty cycles. The effort will require beam-loss control and mitigation to maintain beam losses at less than one watt per meter, as well as multi-megawatt proton sources featuring efficient low-energy acceleration and high beam quality.

New accelerator technology will enhance production of medical isotopes and greatly improve ion-therapy treatment, requiring R&D in accelerators, beam transport, and targetry. An overriding consideration for the next generation of particle therapy facilities will be reduction in the size and costs of the systems, along with simultaneous improvement of reliability standards. New accelerator, transport, and delivery system technologies offer transformative opportunities for proton and ion-beam therapy. Progress in beam shaping and delivery of protons and light ions will reduce radiation delivered outside treatment volumes. Fully optimizing radiation treatments will also require rapidly responding beam delivery systems.

Industrial interests in future acceleration technologies encompass both development and application of new techniques and provision of accelerators and components. The primary factor that inhibits the growth of existing accelerator technology is the dearth of large-scale demonstrations. A user facility where industry could conduct demonstrations in conjunction with potential customers would significantly increase the market for accelerators. Future accelerators will require the industrialization of innovative technologies, such as superconducting radio-frequency cavities and superconducting magnets. Readying U.S. industry to meet the significant demand for superconducting radiofrequency technologies over the next five years will require formal, coordinated technical and industrialization programs between government and industry.

Accelerator R&D for security and defense emphasizes low-cost, compact accelerator systems that are energy efficient, rugged and highly reliable. These compact accelerators will ensure adequate field deployment for both military purposes and national defense. Construction of these fieldable accelerators will require research in all major accelerator components (sources, accelerating cavities, radiofrequency supply, and beam transport). Furthermore, to support development of these compact, high-power systems there is a particular need for updated and improved simulation tools.

Each sector of discovery science requires research and development to reach the next level of sensitivity and discovery. In the general area of accelerator characteristics, reliable and predictable operations will have an enormous impact on scientific progress. Similarly, as energies and intensities increase, efficiency will become increasingly important. Technological progress would yield enormous benefit across the full panoply of research and development topics: radiofrequency power sources, superconducting cavities and ion sources, polarized and unpolarized high-intensity sources, high-field magnets, targetry, higher accelerating gradients, new techniques for cooling and controlling beam, and laser technology.

ACCELERATOR R&D: NEEDS AND OPPORTUNITIES

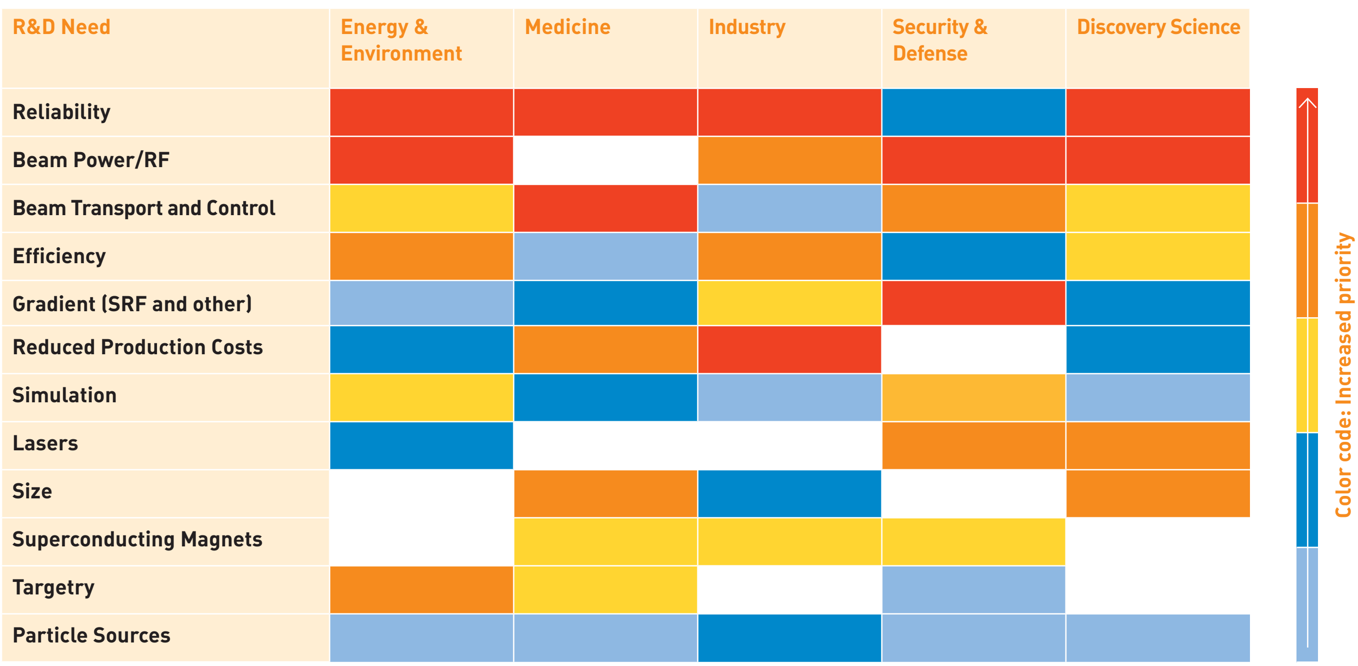
Achieving the advances in accelerator technology discussed in this report will require substantial research and development. Some of this R&D is well defined, some is conceptually developed but needs a broader approach to identify solutions, some is less well developed, and some is purely speculative.

R&D for the development of new or enhanced technologies and for major advances in accelerator performance includes:

- High-gradient superconducting radio-frequency structures. Such structures provide high accelerating fields at extremely large quality factors, minimizing required radio-frequency power to operate, allowing continuous-wave, or cw, operation at 100 percent duty cycle, and limiting operating costs. This makes very large linear accelerators, providing maximum beam power at a given energy, feasible and affordable. Optimizing field levels and quality factors, new materials and surface treatment, cw radio-frequency power supplies and couplers, and cavity structures for different beam velocity ranges all require R&D.
- High-gradient normal conducting radio-frequency structures. Such structures, due to the lower quality factors, are generally operated in pulsed mode but can in principle provide the highest accelerating fields. In situations where the environment does not tolerate complex cryogenic configuration and ruggedness of the accelerator is of highest priority, normal-conducting radio-frequency accelerators are the tools of choice.
- Wakefield technology to miniaturize accelerators with ultra-high-gradient acceleration. This novel concept involves either a laser or an electron-beam pulse propagating through charged plasmas or a dielectric tube, exciting a wake field of the order GeV/m at the speed of light and accelerating following beam bunches or plasma particles.
- High power radio-frequency and pulsed-power generators. Increased beam power, continuous wave to highly pulsed, is needed for applications of intense average beams as well as the generation of short-term extreme environments, requiring advanced high-current versions of linear-transformer-driver technology and radio-frequency power amplifiers.
- Beam phase space optimizations. Developments include high-intensity, small-emittance, high-brilliance, long-lifetime beam sources for electrons and ions, and charge breeding. They also include novel (coherent electron beam and laser) beam cooling techniques, in particular for high-energy primary and secondary beam particles (hadrons, ions, muons). And they include radiation coherence with control of temporal and energy quality in light sources and free electron lasers.

- Beam control and beam loss reduction. The high-current accelerators envisioned for novel uses in several areas require new levels of control of beam losses and instabilities, including advanced beam diagnostics and analysis methods, reliable computer models and verification tools, and novel beam distribution control and feedback systems.
- Superconducting magnets and advanced materials. Advanced superconducting magnet design promises novel, cost-effective, high-field magnet configurations. The use of high-temperature superconductors could sharply reduce cryogenic requirements if mechanical and engineering requirements in accelerators can be met. More broadly, new or modified materials could provide major advances that reach from higher accelerating fields in chemically treated superconducting cavities to photo cathodes for electron beams optimized for brightness and lifetime.

Areas of R&D identified by each working group. All areas are of importance to each working group. Color coding indicates areas with greatest impact.



Any given R&D activity often relates to several advanced accelerator concepts and applications. Similarly, several specific R&D activities may critically enter a specific accelerator scheme. In this respect, necessary R&D also connects to the broad concepts of novel accelerator designs and capabilities. These include:

- Plasma-wake-based, ultra-high-field accelerators
- High-power, high-energy, superconducting proton (ion) driver linacs for medical, fission and fusion energy, security, and environmental applications and for discovery science
- Highest-power (high-intensity, low-energy) electron accelerators for electron and x-ray material irradiations, security and environmental applications
- High-luminosity advanced colliders for electron-electron, proton-proton, electron-ion, and muon-muon collisions, including advanced cooled (unpolarized and polarized) beams
- Future light sources with orders of magnitude improvements in one or more key capabilities, such as radiation coherence, spectrum coverage, photon power, and temporal structure, and based on architectures of free electron lasers, energy recovery linacs, "ultimate" storage rings, and laser-driven sources.

A further important goal in accelerator R&D that cuts across all disciplines is the development of smaller, more compact but often high-power, more rugged ("fieldable"), highly reliable (reflecting industrial standards), and less costly (in construction and operation) accelerator structures. This involves the full range of R&D, from novel concepts and technologies to new materials and advanced engineering.

POLICY AND PROGRAM DIRECTIONS

Policy initiatives also play a significant role in accelerator research and development. As with the technical aspects, common suggestions for policy directions to support accelerator development emerged from the working group reports and findings. These policy directions included creation of demonstration user facilities, improved interagency and interprogram communication and collaboration, and strengthened accelerator education programs. Addressing these policy issues will foster transformative impacts of future accelerator developments and hasten the deployment of those transformations to meet national needs.

Without exception, each group strongly advocated the creation of large-scale demonstration and development facilities to help bridge the gap between development and deployment. The Energy and Environment group recommended demonstrations of electron-beam accelerator flue-gas and water treatment to prove to regulators and potential users that the technology is ready for field deployment. The Medicine Working Group said such facilities are necessary to promote the development of new clinical therapies associated with heavy-ion beams, presently too expensive for industry to initiate. The Industry Working Group suggested that government-sponsored demonstrations of accelerator applications would speed to market energy-efficient applications that replace thermal treatment processes. Security and Defense cited the need for an array of readily available facilities (accelerators, synchrotron light sources, and neutron sources) to characterize chemical, biological, explosive and nuclear materials. Discovery Science reported that facilities are necessary to foster advancement in basic accelerator science and promote training of accelerator scientists.

Similarly, there was a widespread call for improved interagency, inter-program, and industry-agency coordination. Deployment of accelerator-based contributions to energy and the environment will require both interoffice and internal cooperation. For instance, development and study of accelerator-driven power generation or transmutation of nuclear waste would benefit from coordination between DOE's Office of Nuclear Energy and Office of Science. Similarly, development of beam therapy would benefit from coordination between the National Institutes of Health and DOE's Office of Science. An important finding of the Security and Defense group is that an integrated national program in accelerator R&D, presumably involving DOE and the Department of Defense, is critical for meeting the challenges of future security and defense. State-of-the-art scientific accelerators naturally benefit from coordination among several program offices within DOE's Office of Science, which should naturally strengthen with the development and construction of the next generation of discovery machines. Strengthened relationships between industry and the program offices of DOE, through workshops, organizations and integrated planning, would encourage the development and use of accelerators to meet national needs in many areas. Areas appropriate for industry-agency coordination are industrialization programs, technology transfer and intellectual property rights.

The working groups also strongly highlighted the value of expanded training and education of accelerator scientists and engineers and the recognition of accelerator science as a scientific discipline. Continued U.S. innovation in basic accelerator research and in the areas of energy and environment, medicine, industry, security and defense, and science rests on the next generation of accelerator scientists. The motivations for strengthened educational efforts include training of the next generation workforce, engaging the best and the brightest students and early-career scientists and engineers, and workforce training for new applications. Attracting the caliber of scientific minds essential for progress in the field requires a vibrant program of accelerator science and technology research, world-class training facilities, and attractive instructional opportunities. Universities should be encouraged to offer courses in the practical uses of industrial accelerator technologies as well as in the discipline of accelerator science. These activities should strongly link to initiatives establishing accelerator demonstrations and user facilities. There was little quantitative analysis of the national need for accelerator scientists and skilled technicians, suggesting that future directed studies may be appropriate.

The workshop's report enumerates the most pressing needs of research and development for accelerators in the many areas examined. It emphasizes that no federal agency can respond to the many needs by itself, requiring interagency collaboration, collaboration with industry through partnerships, the need for test facilities, and stronger theoretical research and simulation efforts in accelerator physics.

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Security and Defense

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William Reed, *Varian*
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Kees de Jager, *JLAB*
Oliver Kester, *MSU*
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