# Particle beams behind physics discoveries

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Citation: Physics Today **73**, 4, 32 (2020); doi: 10.1063/PT.3.4452
View online: https://doi.org/10.1063/PT.3.4452
View Table of Contents: https://physicstoday.scitation.org/toc/pto/73/4
Published by the American Institute of Physics

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# Particle beams behind physics discoveries

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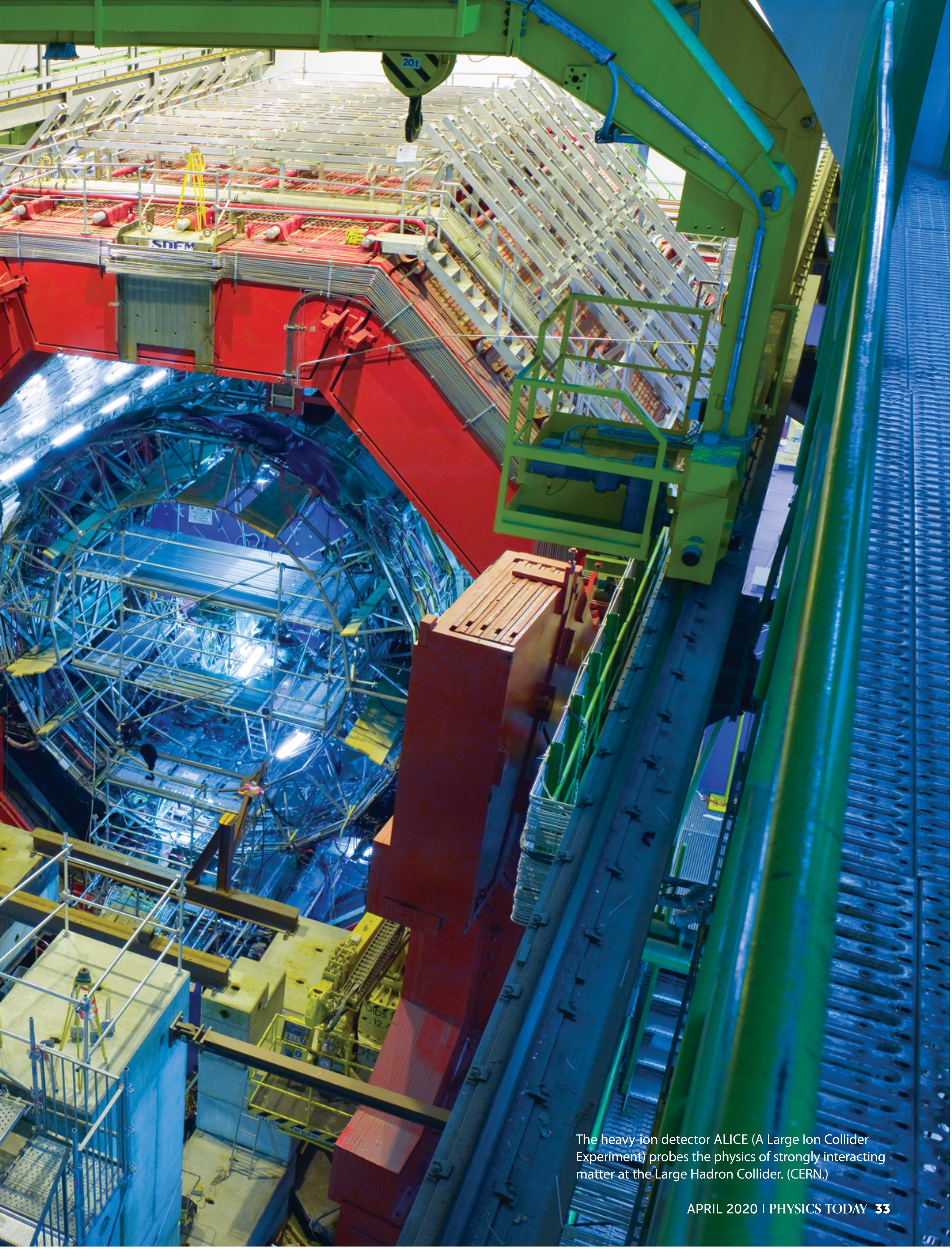
**Advances in accelerator technology are enabling discoveries in particle physics and other fields.**

A team of accelerator physicists came to the CERN Control Center, shown in figure 1, on the night of 30 June 2017. Some members came from departments and groups throughout CERN; others, like me, even came from across the ocean. Our aim was to test a new collimation idea for the Large Hadron Collider (LHC) beam that would be critical for the future of the world's most powerful accelerator. An eight-hour shift was scheduled for beam-physics studies. As is often the case at large accelerator facilities, beam physicists get full control of their machines overnight to minimize the inconvenience to users and high-energy physicists and to avoid numerous daytime distractions.

## One night in the life of an accelerator physicist

We were scheduled to get beam access at 10:00pm, but due to last-minute problems with the collider's cryogenics, we had to wait until well beyond midnight. Stefano Redaelli, head of the LHC collimation group and my close long-term collaborator, had been planning the night's study for months. He and I repeatedly reviewed the detailed step-by-step procedures of the study over several cups of coffee from the control center's famously great espresso machine.

The LHC has more than a hundred collimators—1.2-m-long fiber-reinforced graphite plates—to intercept stray protons.[1] They protect the machine's 8 T superconducting magnets and other sensitive equipment from damage by any of the central beam's 6.5 TeV protons that get kicked away from their orbit. That happens when protons collide with either residual gas molecules inside the high-vacuum beam pipe or the opposite-direction proton




The heavy-ion detector ALICE (A Large Ion Collider Experiment) probes the physics of strongly interacting matter at the Large Hadron Collider. (CERN.)

MAXIMILIEN BRICE/CERN

**FIGURE 1. THE CERN CONTROL CENTER** is made up of four "islands" in one big room. Each island has a circular arrangement of consoles and displays. They control the Large Hadron Collider (above), the Proton Synchrotron and Super Proton Synchrotron in the collider injection chain, and the technical infrastructure of the CERN accelerator complex.

beam at an interaction point inside one of the massive particle detectors.

The collimator jaws are the closest objects to the 500 MJ 0.2-mm-diameter beams; they come within just a few millimeters of each other. Although the graphite jaws are very robust—they can absorb the power from the stray beam and survive—their electrical conductivity is relatively low, which means that acquired charge can't easily dissipate. After its next major upgrade, the LHC will produce much higher beam currents, and graphite collimators, if not modified, would lead to unstable transverse oscillations of the proton beams. The night's plan was to test a new type of collimator that would mitigate the issue by covering the graphite surface with a 5-μm-thick layer of much-higher-conductivity material. We had prepared three 10-mm-wide parallel strips of molybdenum carbide, titanium nitride, and pure molybdenum. By placing the LHC beam next to each strip in turn, we expected to see up to threefold improvement in the beam stability.

As soon as we got the beams from the LHC injectors, we slowly accelerated them for more than 20 minutes until they reached the operational energy of 6.5 TeV. Then the fun began. In a controlled fashion, we moved the proton beams toward and away from each strip in an attempt to observe changes in the frequency of the beams' transverse oscillations. We established the best procedures relatively quickly and began the planned tests. By about 5:00am we were done, and the next team of accelerator physicists started to appear in preparation for their beam time, which was scheduled to start at 6:00am. We reviewed the preliminary results of our measurements with delight: The effect was within 10–15% of what was anticipated, and the beam was most stable near the pure Mo strip, which had the best conductivity.

I left Geneva on a 7:00am flight to Chicago. Over the next several months, the data we collected were analyzed, compared with computer models, presented at a major international conference, and published. Most importantly, our approach was found to be viable, and Mo-coated collimators were approved as part of the billion-dollar High-Luminosity LHC (HL-LHC) project scheduled for implementation by 2026.

## Innovation leads to improvement

The LHC is the most complex scientific instrument of our time, but its life cycle is the same as that of previous frontier machines (see figure 2). They all were designed, constructed, and commissioned, and then they underwent many years of incremental improvements in luminosity. The early and middle years of a facility's life are dominated by the quest for ever higher luminosity and are often characterized by a repeating cycle of problems and solutions. The Tevatron proton–antiproton collider at Fermilab had the longest tenure at the energy frontier of particle physics, from October 1985 to September 2011. More than 40 improvements in beam physics and technology during that time enabled the Tevatron's peak luminosity to reach 430 times its original design value.[2] A few of the improvements resulted in gains of as much as 25–40%, although many added as little as 5%.

Many upgrades can be done during operation and usually at a limited cost to the physics program. More significant gains, like the factor-of-three increase in the LHC's performance expected during the forthcoming HL-LHC era, require years of preparation and hardware installation to either increase beam currents, tighten the beam's focus at interaction points, or both. Notably, there are remarkably long periods of sustainable exponential growth in luminosity $L$, indicated by near-linear segments of data seen in figure 2. The performance of energy-frontier colliders has increased by a factor of $10^4$ from the 1970s until now with an average doubling time $\tau_L = dt/d\log_2(L)$ of approximately 4 years. For comparison, Moore's law says that the number of transistors per microprocessor chip should double every two years. Given the complexity and size of modern accelerators, such a fast pace is astounding.

Beam physicists are the people who make that increase happen. In addition to supporting constant accelerator operation, they continuously invent and implement new ideas and methods while also improving existing ones. In the 21st century alone, beam physicists have developed a dozen advanced tools for high-energy hadron and electron–positron colliders, some with strange-sounding names like "crab waist," "electron lenses," "nanobeams," and "crab cavities."

Beyond particle physics, accelerators are major tools for basic and applied research worldwide (see the box on page 35). They generate electromagnetic radiation from terahertz waves to x rays by moving high-energy electrons in magnetic fields. The ability of an x-ray source to probe molecules' atomic structures for biology and materials research scales with its brilliance, which embodies not only the photon flux but also the beam's collimation.[3] Brilliant beams are intense and tight. Figure 3 shows how the brilliance of radiation sources has increased over time. Modern synchrotron light sources are $10^{11}$ times brighter than those used to generate x rays in hospitals, and free-electron lasers offer an additional 10-orders-of-magnitude increase in brilliance. The increase by a factor of about $10^{22}$ from the mid 1960s to the present gives the average doubling time of about eight months—three times as fast as for transistors and six times as fast as the luminosity of colliders.

The origin of that dramatic improvement is the sustained evolution of technology for producing radiation from moving electrons. First- and second-generation synchrotron radiation sources used the by-product light from electron ring accelerators. However, in the past two decades, some 40 dedicated third-generation facilities known as storage rings have been built worldwide with the deliberate purpose of generating high-brilliance x rays. They use specially designed insertion devices called undulators that shake the beam to increase the emission of electromagnetic radiation and can simultaneously deliver x-ray beams to many, often several dozen, experimental stations.[4]

A radiation source's brilliance can be increased by the optimal design of its underlying technology: the electron beam in the storage ring. In the past decade, beam physicists have developed numerous improvements, such as cutting-edge superconducting undulator magnets and advanced systems to stabilize beam orbits down to as small as a few nanometers. One impressive recent invention is the so-called multibend achromat focusing lattice, which optimizes the arrangement and strengths of the dipole, quadrupole, and sextupole magnets used to guide a beam. The lattice can make electron-beam sizes and angular divergences so small that the phase space of radiated photons is limited only by diffraction. That upgrade increases the brilliance of fourth-generation sources, also known as diffraction-limited storage rings, by two to three orders of magnitude over the previous generation.

The most recent revolution in radiation production has been the self-amplified spontaneous emission in linear-accelerator-

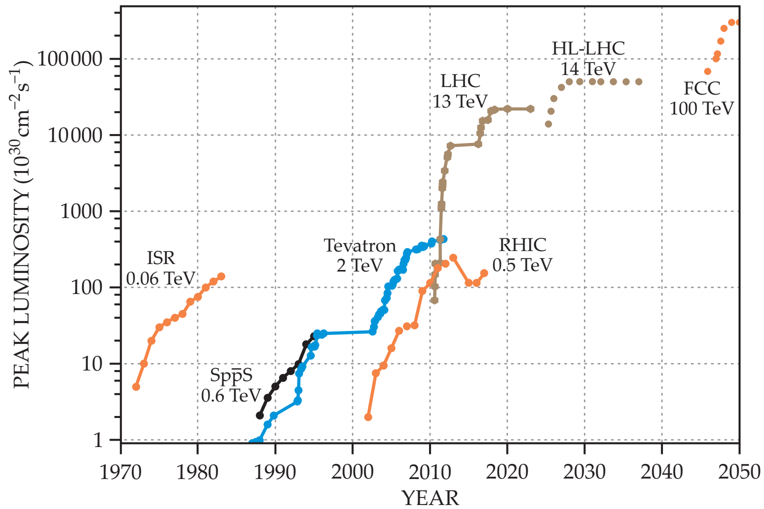



**FIGURE 2. A COLLIDER'S LUMINOSITY** quantifies its ability to generate new particles via high-energy collisions. The production rate for a particle of interest is the product of the beam luminosity and the cross section for the desired reaction. Producing high luminosity generally requires high-intensity beams to be compressed so they collide with the smallest possible overlap area. For reference, at the Large Hadron Collider's 2019 luminosity, about one Higgs particle is born every second when two 6.5 TeV proton beams collide inside the ATLAS and CMS detectors (see the article by Joe Lykken and Maria Spiropulu, PHYSICS TODAY, December 2013, page 28). All luminosities shown are for proton–proton and proton–antiproton colliders. (Courtesy of Vladimir Shiltsev.)

## THE INFLUENCE OF ACCELERATOR SCIENCE ON BASIC RESEARCH

In 2011 SLAC researchers Enzo Haussecker and Alexander Chao set out to evaluate accelerator science's impact on the physics community.[12] They analyzed all of the Nobel Prize–winning research in physics from 1939—the year Ernest Lawrence received his for inventing the first modern accelerator, the cyclotron—until 2009. Updating the numbers to account for the 2010–18 awards does not change their main conclusion: Accelerator science has been integral to physics research. It inspired or facilitated work by 25% of physicists working between 1939 and 2018; on average, accelerator science contributed to a physics Nobel Prize every three years. Two more prizes for accelerator science were awarded after Lawrence's in 1939: John Cockcroft and Ernest Walton won in 1951 for inventing the linear accelerator, and half of the 1984 prize went to Simon van der Meer for developing the method of stochastic cooling. Several other developments are widely recognized as Nobel caliber. One is the 1952 discovery of the principle of strong focusing, in which a beam of charged particles passes through alternating magnetic field gradients and converges. It is now used in the majority of accelerators. Another is the invention of free-electron lasers, and particularly self-amplified spontaneous emission FELs, which revolutionized x-ray-based research.

Accelerator-based synchrotron radiation sources have also been instrumental to the work of several scientists who were awarded a Nobel Prize in Chemistry: John Walker in 1997 for revealing the structure of F1-ATPase, Roderick MacKinnon in 2003 for demonstrating the structure of cellular ion channels, Roger Kornberg in 2006 for determining the structure of RNA polymerase, Ada Yonath in 2009 for discovering the structure and function of the ribosome, and Brian Kobilka and Robert Lefkowitz in 2012 for studying G-protein-coupled receptors.

The US Department of Energy's Office of Science is a major supporter of 28 user facilities for basic research; for more information see www.science.osti.gov/user-facilities. Of those facilities, 16 are accelerators—colliders, light sources, and neutron sources. The annual budget for their operation and construction exceeds \$2 billion. They support about 20 000 users from academia, industry, and government laboratories. Some 400 scientists and students carry out beam-physics research at a dozen dedicated accelerator R&D facilities.

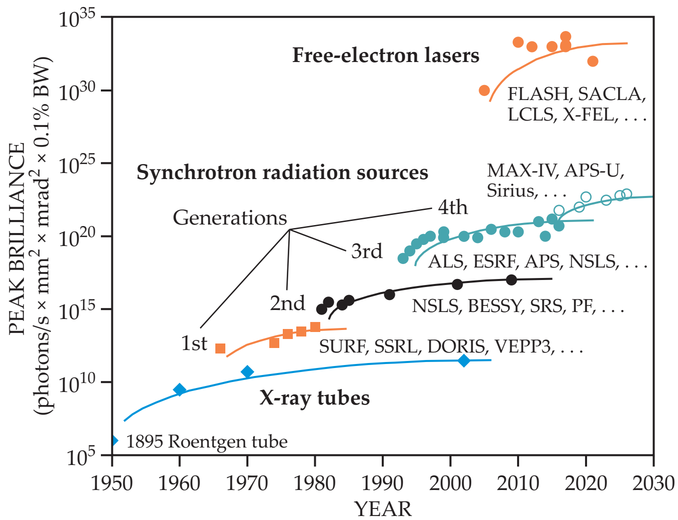



**FIGURE 3. THE PEAK BRILLIANCE OF VACUUM-UV AND X-RAY SOURCES** has grown tremendously since Wilhelm Roentgen's discovery of x rays in 1895. Electron storage rings are centerpieces of the first-, second-, third-, and fourth-generation synchrotron radiation sources. High-current electron linear accelerators drive free-electron lasers. (Adapted from ref. 10.)

driven x-ray free-electron lasers. The lasers' higher brilliance relative to the storage-ring-based sources is due to their extremely short and intense light pulses, which are generated by a small, relativistic electron beam passing through an alternating magnetic field in a long undulator array and coherently pumping its own radiation. Proposals are under consideration for high-efficiency x-ray sources based on energy-recovery linear accelerators, or linacs. Those sources would combine the advantages of both ring- and linac-based schemes.

Secondary particles can be generated in abundance when high-energy beams hit solid or liquid targets. Those particles can subsequently be used in such applications as muon spectroscopy, neutrino physics, and neutron scattering. A secondary particle beam comes from either a linac, cyclotron, or synchrotron, and its intensity is proportional to the power of the primary beam. Over the past decades, scientists have been able to increase that power by about three orders of magnitude (see figure 4) by improving technology and addressing problems with beam pulse structures, beam losses, and the lifetimes of beam targets.

## Technology push

The mid 20th century saw a burst of accelerator construction because accelerators could finally produce beams with energies per particle exceeding those of nuclear reactions and lasers by many orders of magnitude.[5] Even so, over the past 50 years the record-high beam energy has advanced at a slower pace than total beam power, luminosity, and peak brilliance. The energy frontier progressed from about 60 GeV at CERN's Intersecting Storage Rings accelerator in the early 1970s to 13 TeV at the LHC in 2019, for a doubling time of approximately 6 years. The main cause of high-energy accelerators' relatively slow progress is their cost, which depends strongly on their core technologies. Figure 5 shows the present snapshot of the "accelerator menu."

The cost and affordability of accelerators accounts for the spectrum of their types: 99% of the more than 30 000 accelerators in operation worldwide are relatively small with low beam energies. They are used for commercial production of radionuclides and radiopharmaceuticals, ion implantation, energy and environmental applications, neutron generation, lithography, studies of material interfaces, and other production issues in the semiconductor industry. (See the article by Robert Hamm and Marianne Hamm, PHYSICS TODAY, June 2011, page 46.) Even research facilities have more x-ray and light sources—about 60 worldwide—than particle colliders, of which there are only 7. Just two have energies over 100 GeV, the Relativistic Heavy Ion Collider at Brookhaven National Laboratory and the LHC at CERN.

Frontier particle accelerators often cost more than $1 billion, and the aspirations of high-energy-particle physicists require even larger facilities estimated to cost 10 times that. Such expenses become nonnegligible on the scales of national economies. All kinds of measures are taken to cut costs, including reuse of existing accelerators as injectors for new ones, other utilization of existing infrastructure, and burden sharing among several laboratories or countries, as with CERN. Major opportunities for new facilities come from better technological performance, reduction of cost, or, ideally, both.

Current core technologies employ normal and superconducting magnets and normal and superconducting RF cavities to accelerate particles (see figure 6). The magnets either focus or bend beams in circular accelerators, and the time-varying electric fields in RF cavities accelerate the charged particles. Tunnels, electrical infrastructure, and facilities' other technical subsystems can be quite expensive; however, the cost of core accelerator components, magnets, and RF structures usually dominates construction costs for high-energy and high-power accelerators. Over the past quarter century, the accelerator community has successfully worked to bring those costs down. Peak magnetic fields in operational accelerators grew from

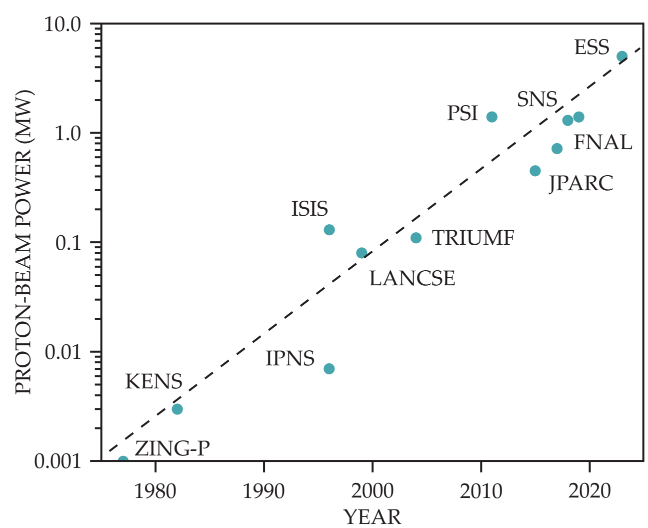



**FIGURE 4. BEAM POWER IN LEADING PROTON ACCELERATORS** has increased dramatically over the past few decades. The dashed line corresponds to the doubling time of about four years. (Adapted from ref. 11.)

about 4 T to 12 T. Accelerating electric gradients have reached record highs, increasing by a factor of three or so to more than 30 MV/m in superconducting RF cavities and to more than 100 MV/m in normal-conducting RF structures. Without improvements in magnet and RF technologies, costs would have grown linearly with beam energy $E$; instead, the costs of modern facilities[6] have grown approximately as $\sqrt{E}$. Still, the growing demand for higher-energy beams has outpaced the progress of traditional accelerator technologies, so researchers continue to pursue new ideas and technological advances.

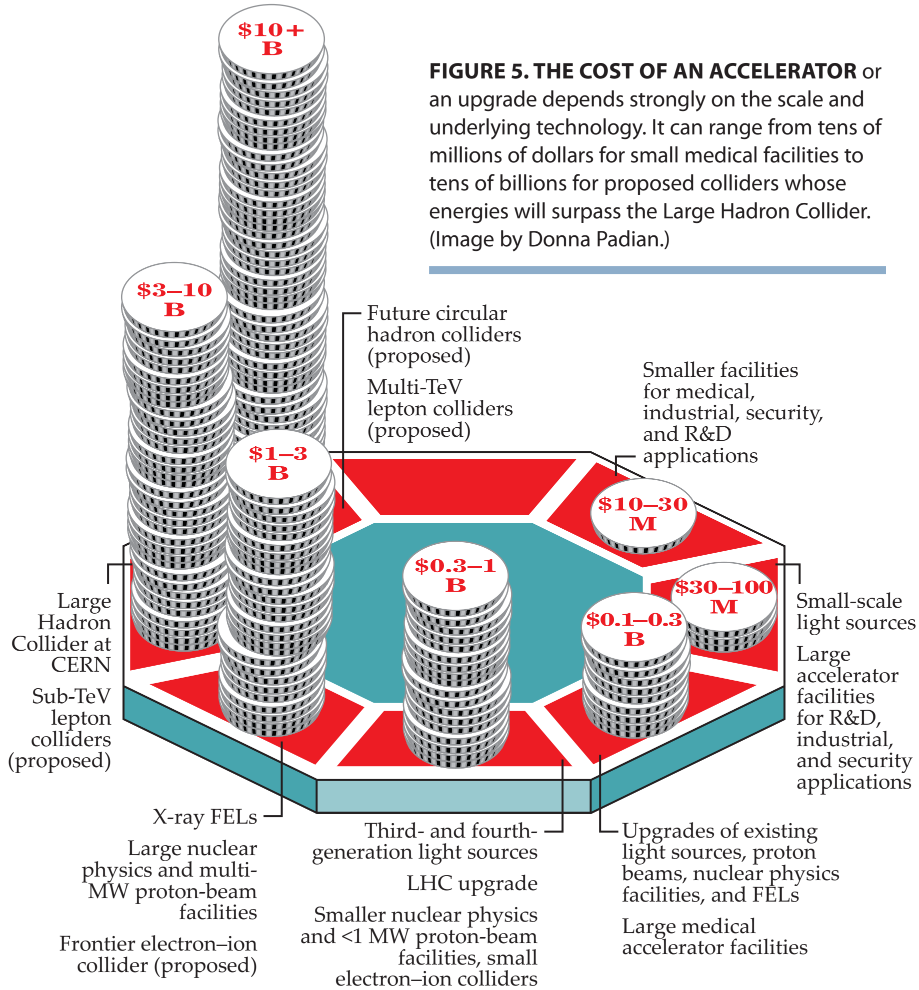



**FIGURE 5. THE COST OF AN ACCELERATOR** or an upgrade depends strongly on the scale and underlying technology. It can range from tens of millions of dollars for small medical facilities to tens of billions for proposed colliders whose energies will surpass the Large Hadron Collider. (Image by Donna Padian.)

## Beams as science

Today, around 4500 accelerator scientists and engineers work in more than 50 countries. They collaborate with a pool of approximately three times as many technical experts. Although most of us are deeply involved in operations and ongoing upgrades, the career of an accelerator scientist also includes design and construction of new facilities, beam-physics research, development of critical technical components, and project leadership. It also often involves technology transfer, industrial applications, education and training of the next generation of accelerator experts, and outreach to both the public and academia.

Over the past 20 years, the science of beams has evolved into a distinct discipline with its own subject matter and methods of study, a series of annual International Particle Accelerator Conferences with a typical attendance of about 1500, almost two dozen other regularly held conferences and workshops on topics ranging from computer modeling to accelerator technologies, and dedicated peer-reviewed journals—the leading one, *Physical Review Accelerators and Beams*, reached its 20-year anniversary in 2018.

Several thousand people, including nearly 1400 in Europe and approximately 400 in the US, receive some training in accelerator and beam physics annually.[7] About 40 academic programs at universities worldwide, including a dozen each in the US and Europe, provide that training. However, education for accelerator physicists and engineers also includes on-the-job training supplemented with intensive courses at numerous locations, through programs such as the US Particle Accelerator School and the CERN Accelerator School. Approximately 100 PhDs are awarded each year globally in accelerator and beam physics.

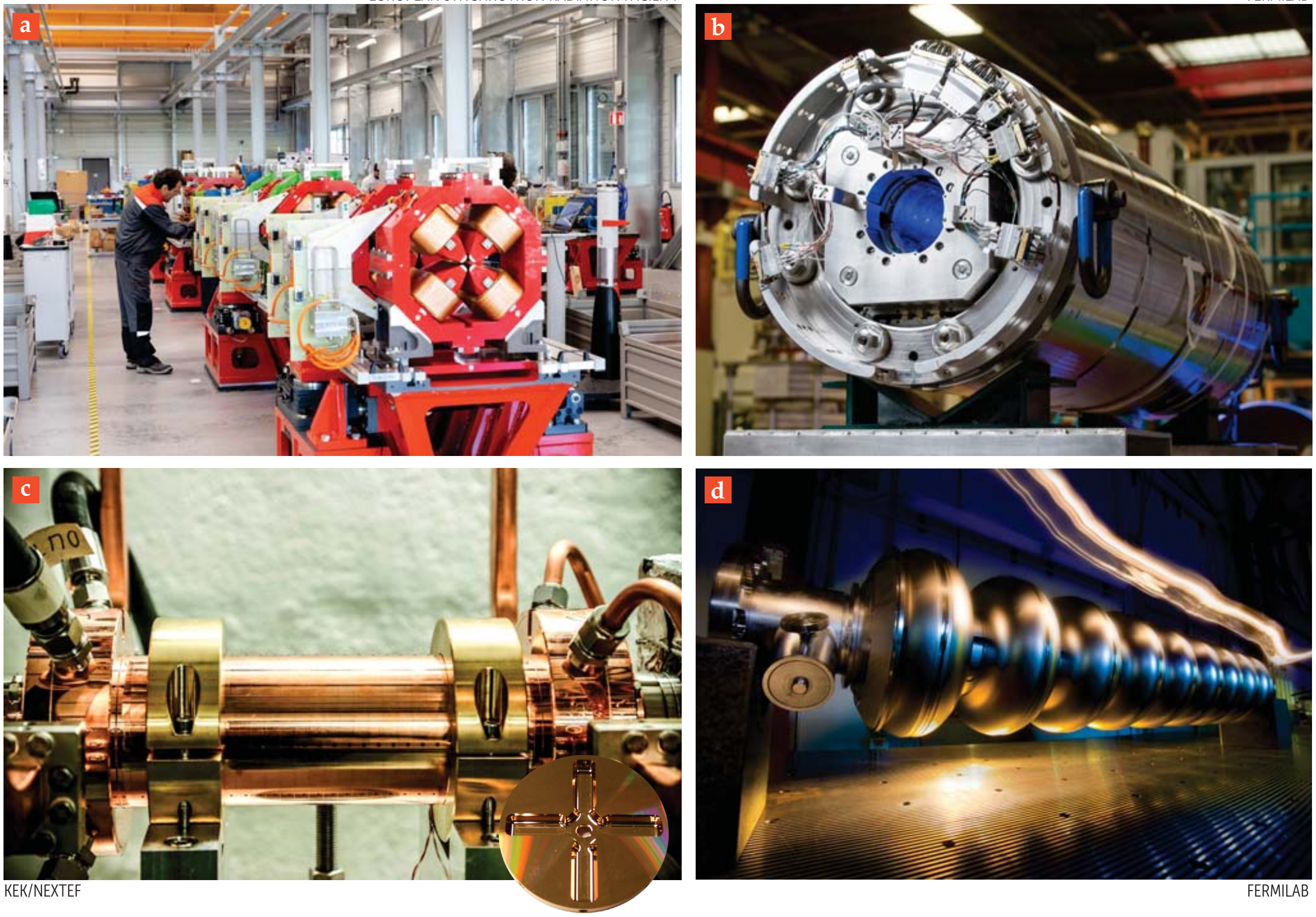
Accelerator scientists are well represented in many scientific societies, councils, and groups worldwide. The International Union of Pure and Applied Physics Working Group 14 has been promoting the exchange of information and views among the members of the accelerators and beams community since 2015, and the International Committee for Future Accelerators has been facilitating collaboration on the construction and use of high-energy accelerators since 1976.

In the US, funding for accelerator science and technology totals approximately $120 million per year from the Department of Energy's Office of Science—which includes programs for high-energy physics, basic energy sciences, and nuclear physics—and from NSF. The high-energy-physics program is by far the largest sponsor, with about 5% of its annual budget going to general accelerator R&D. Large, dedicated beam-research facilities are hosted by major national laboratories, including Fermilab, SLAC, Lawrence Berkeley, Argonne, and Brookhaven, and several universities, including Cornell, UCLA, the University of Michigan, and the University of Maryland. Those facilities play pivotal roles in the progress of accelerator science.

The biggest challenge for us accelerator physicists is developing energy-frontier beams. If we were to use current technology, however, the cost of constructing colliders with substantially higher energy would be prohibitive. We're unlikely to find the money, or find a site where labor, land, and raw materials are cheap, to pursue that route.

Instead, we are exploring several avenues for development. One approach is using traditional superconducting magnets and RF cavities to accelerate nontraditional particles—namely, muons. Unlike protons, which share energy between constituent quarks and gluons, muons are point-like particles that effectively deliver their entire energy to the collision. The center-of-mass energy in muon–muon collisions will be 6–10 times that in proton–proton collisions at the same beam energy, so a 14 TeV muon collider would be approximately equivalent to a 100 TeV hadron collider. Circular electron–positron colliders at

EUROPEAN SYNCHROTRON RADIATION FACILITY FERMILAB




KEK/NEXTEF FERMILAB

**FIGURE 6. STATE-OF-THE-ART CORE ACCELERATOR TECHNOLOGIES** enable scientists to control beams. **(a)** Sophisticated normal-conducting magnets for the European Synchrotron Radiation Facility's multibend achromat upgrade include combined-function dipoles with quadrupolar components to simultaneously bend and focus the electron beam. Quadrupoles, sextupoles, and octupoles control the beam's size and other properties. **(b)** A 12 T superconducting large-bore niobium–tin quadrupole magnet, shown on a test stand at Fermilab, is a prototype for the High-Luminosity Large Hadron Collider upgrade. **(c)** A 12 GHz conducting copper RF cavity, shown at the KEK accelerator research facility in Japan, was developed for the CERN Compact Linear Collider project; the inset shows one damped accelerating cell. **(d)** A superconducting 1.3 GHz accelerating structure with nine cell cavities was developed for the International Linear Collider. It produces a 31.5 MeV/m beam-accelerating gradient.

such energies are impractical because they would lose tremendous energy as synchrotron radiation, but much heavier muons avoid that problem. Researchers have been developing that strategy for the past 20 years (see the article by Andrew Sessler, PHYSICS TODAY, March 1998, page 48) and have now proved the conceptual feasibility of an energy-frontier muon collider. One necessary advance—ionization cooling of the initially dispersed muons—was experimentally demonstrated in 2019. Still, many formidable challenges remain before we can definitively assess the technical and cost feasibility of such a collider; most of those challenges involve the effective and economical production of high-brightness muon beams.

Continuing to improve existing technologies is a less revolutionary approach, but it also has some promise. Assuming that next-generation energy-frontier beams are 15–20 years away and the rate of progress will not slow down, doubling or even tripling current energy records seems possible. Many ideas already exist for achieving 20–24 T magnetic fields with high-temperature superconductors and reaching 60–90 MV/m accelerating gradients with superconducting RF cavities. Experimental proof-of-principle demonstrations of such techniques must be undertaken to establish their potential to make future machines feasible and affordable. Long-standing collaborations with the solid-state physics and industrial technologies communities will greatly help with those developments.

One of the biggest advances may come from the novel technology of particle acceleration by plasma waves, which are excited by either lasers or particle beams. The field has advanced and expanded in the past two and a half decades with the influx of methods and ideas from plasma and laser scientists;[8] Gérard Mourou and Donna Strickland were awarded the 2018 Nobel Prize in Physics for related work (see PHYSICS TODAY, December 2018, page 18). The total electron energy gain in a 1-m-long plasma cell has progressed from a few MeV to 9 GeV with an energy-doubling time of about 2.5 years.[9]

At the same time, researchers have developed a better understanding of what would be required to build a collider based on plasma acceleration (see the article by Wim Leemans and Eric Esarey, PHYSICS TODAY, March 2009, page 44). The current focus of plasma acceleration R&D is less on developing record-breaking accelerating gradients and more on addressing mundane but critical issues such as energy-transfer efficiency, multistage acceleration, preservation of high brightness and energy in electron and positron beams traveling through dense plasmas, and cost-efficient drivers for plasma waves. We have not yet devised a reliable technical design for an affordable high-luminosity, multi-TeV electron–positron plasma wakefield collider. However, there is reason for optimism: More than a dozen research groups are building and operating test facilities to systematically explore various options and regimes.

## The bottom line

For the January 2001 issue of PHYSICS TODAY (page 36), Maury Tigner, a foundational and pivotal figure in modern accelerator physics, wrote an article entitled “Does accelerator-based particle physics have a future?” He made many observations remarkably close to those outlined above and called on other scientists, particularly particle physicists, to help explore new ideas and improve the cost-effectiveness of our accelerators.

The answer to Tigner’s question was and is resoundingly yes. Beam physics has evolved into a scientific discipline of its own, and the accelerator community has developed outstanding advances such as fourth-generation synchrotron light sources, x-ray free-electron lasers, and megawatt-power proton-beam facilities like spallation neutron and neutrino sources. World records have been set as the performance metrics of major accelerator technologies have doubled or tripled. Improvement of the maximum beam energy has been less dramatic, but the LHC expanded that frontier by a factor of seven and facilitated the discovery of the Higgs boson—the last missing piece of the standard model—in 2012 (see PHYSICS TODAY, September 2012, page 12).

Many advances, breakthroughs, and discoveries lie ahead. The push for improved methods of particle acceleration continues in several directions, including the use of exotic particles like muons, more advanced magnets and RF cavities, and compact high-gradient plasma accelerators. Applications of advances in solid-state physics, lasers, plasmas, and high-energy physics are being explored through collaborations with experts in those disciplines. Accelerator and beam physicists expect that developments currently underway will lead to more effective and economical beam-based research facilities in the coming decades.

*The author thanks Matt Arena, Dmitry Denisov, Peter Garbincius, Heath O’Connell, Qing Qin, and Frank Zimmerman for their input, insightful discussions, and critical comments.*

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