

The beam business: Accelerators in industry

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Particle acceleration techniques originally developed for physics research have found a dazzling variety of uses in manufacturing and commerce.

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Most physicists know that particle accelerators are widely used for treating cancer. But few are acquainted with the depth and breadth of their use in a myriad of applications outside of pure science and medicine. Society benefits from the use of particle beams in the areas of communications, transportation, the environment, security, health, and safety—in terms both of the global economy and quality of life. On the manufacturing level, the use of industrial accelerators has resulted in the faster and cheaper production of better parts for medical devices, automobiles, aircraft, and virtually all modern electronics. Consumers also benefit from the use of accelerators to explore for oil, gas, and minerals; sterilize food, wastewater, and medical supplies; and aid in the development of drugs and biomaterials.

For the purposes of this article, we define industrial accelerators as all charged-particle accelerators that generate external beams for use in any process other than direct medical treatment or basic physics research.¹ Hence we do not exclude the production of therapeutic or diagnostic radio-nuclides, because most of them are now produced by for-profit businesses using commercially built accelerators.

Of the more than 30 000 particle accelerators that have been built worldwide over the past 60 years, more than half have been used for industrial purposes. The number of new systems installed annually by industry is almost twice the number for research and medical therapy. Industrial accelerators are readily available for purchase from commercial firms around the world.

The technology used in most modern industrial accelerators was originally developed in the 1930s for physics research.² Soon after a new type of accelerator was invented, someone recognized its potential for practical applications, often as a direct result of basic research on the interaction of the particle beams with matter. But although the practical uses of a new kind of accelerator are usually explored soon after its invention, its widespread adoption as an industrial tool can take decades. For example, ion implantation of semiconductor materials, now the largest industrial application of accelerators, was first proposed by William Shockley in the 1950s. But it wasn't a widely accepted industrial technique until the 1970s.³

Such lengthy acceptance cycles are common because, in the beam business, the users are primarily concerned with cost-effectiveness. They are less interested in the details of the accelerator's technology; to them, the accelerator is a black box. Most industrial applications have evolved from science programs using research accelerators at universities or national laboratories, and they are generally not engineered to

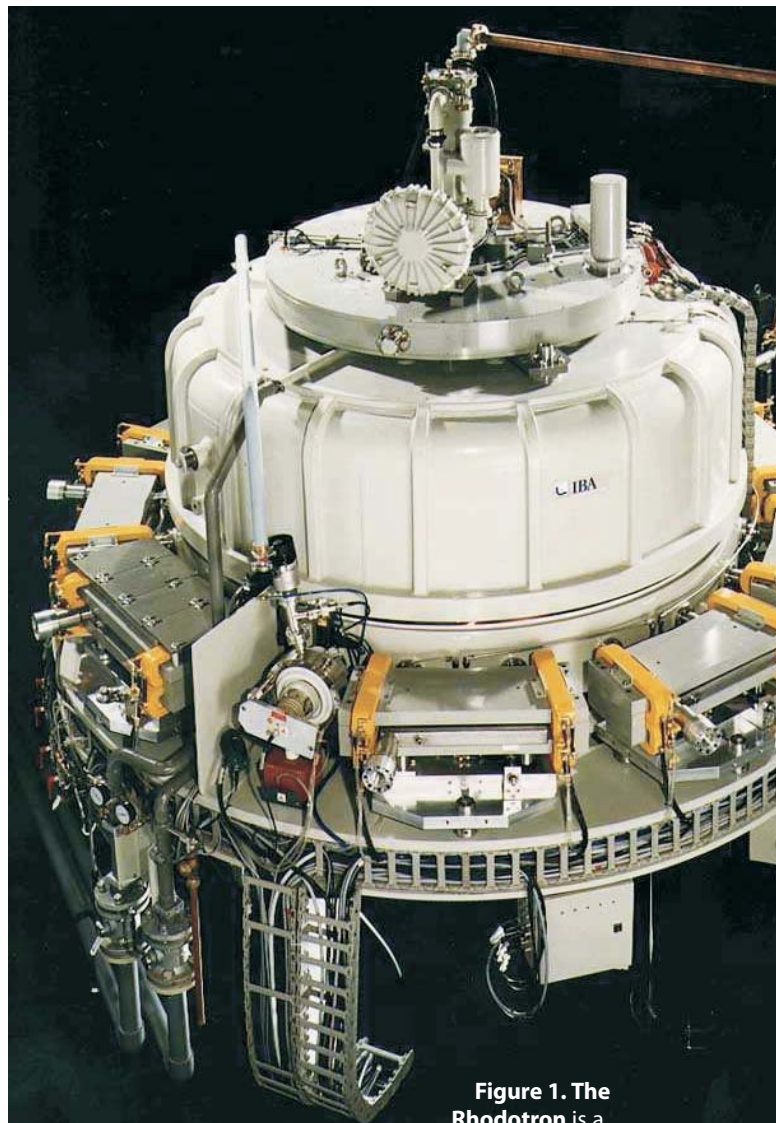


Figure 1. The Rhodotron is a high-power electron accelerator specifically developed for the sterilization of medical products in an industrial setting. These accelerators, about three meters wide, can produce up to 700 kW of beam power at electron energies of 7 MeV. (Photo courtesy of IBA, Louvain-la-Neuve, Belgium.)

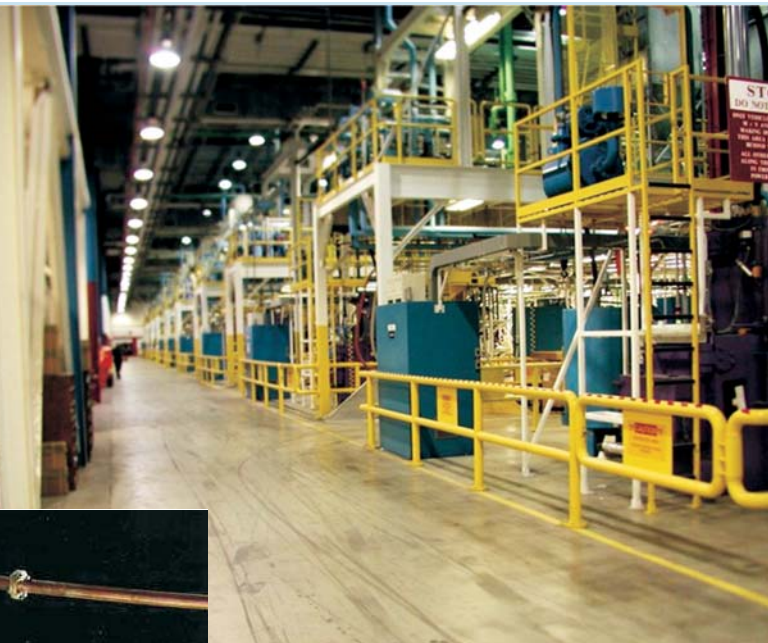


Figure 2. A typical electron-beam processing facility, employing 10 large electron accelerators arrayed in a row of production stations. This facility produces shrink-wrap material. (Photo courtesy of Air Seal Corp, Duncan, SC.)



meet the rigid requirements of routine production. So before a system can be widely accepted by industry, it must first be developed into a reliable production tool and then tested in an industrial setting for a number of years. The performance requirements demanded by industry have, in fact, led to significant advances in accelerator technology.

The accelerators

Industrial accelerators include both electron-beam and ion-beam systems spanning essentially all of the acceleration methods developed for research: electrostatic systems, RF linacs, betatrons, cyclotrons, and synchrotrons.⁴ We only briefly discuss the basic accelerating principles, but we describe in some detail the various types of accelerators employed in a number of industrial applications.

Accelerators can be divided into three broad categories according to the acceleration scheme: direct voltage; linear accelerators with RF voltage; and cyclic accelerators using magnetic fields, with or without RF voltage. Direct-voltage accelerators (also known as DC accelerators) make up the category most widely used in industry for both electron and ion beams. Many use a relatively low DC voltage (300 kV or less) applied across a short gap, with the external power supply connected to the accelerator through a high voltage cable. Among them are ion-implantation accelerators; small, deuteron-beam fusion-neutron generators for the oil industry; and electron-beam systems for materials processing.

The high-voltage power supply is an integral part of higher-energy DC systems such as Van de Graaff accelerators, which use charge-carrying

belts; Cockcroft–Walton generators, which use voltage multipliers; and inductive-core transformers (ICTs).

RF linacs use alternating RF voltage to accelerate either electrons or ions through a series of resonant cavities. Such linacs can generate very high beam currents; they are the second most widely used category for industrial applications, primarily with electron beams. Whereas most RF electron linacs use side-coupled cavity structures and operate at frequencies from 1 to 9 GHz, all modern industrial ion linacs use the RF-quadrupole (RFQ) structure and operate at frequencies from 100 to 600 MHz. Although ion linacs have been used for physics research since the 1930s, only with the development of the RFQ structure in the 1970s did they become practical for industrial applications.

Cyclic accelerators are not yet as widely used in industry as linacs and DC machines are. Cyclotrons are the oldest and most commonly used form of cyclic accelerator. Because mass-dependent relativistic effects make it impractical for them to accelerate electrons to useful energies, they are used only to accelerate ions. A magnetic field confines the ions in an outwardly spiraling path as they are accelerated by the RF voltage. High-energy cyclotrons (with ion energies above 200 MeV) are used to treat cancer, but their lower-energy cousins are used in industry primarily for the production of radionuclides. Because that requires higher beam currents than could be produced by early research machines, it has led to significant advances in cyclotron technology. Among such advances are the acceleration of negative ions for better beam extraction and the use of large-gap, strong-focusing magnets to minimize beam losses.

The betatron is the next oldest technology in the cyclic category. It was developed to accelerate electrons to high energies using only a time-varying magnetic field. Many betatrons have been built for nondestructive testing and medical applications, but they have now been replaced for those applications by compact modern electron linac structures. Nowadays, betatrons are used only to create high-energy x rays for industrial radiography.

The Rhodotron is a newer cyclic accelerator, designed to accelerate high currents of electrons using a coaxial resonator to achieve an energy boost of 1 MeV per pass. Bending magnets arrayed around the circumference of the cavity constrain the beam to make repeated passes through the accelerating cavity. The Rhodotron, shown in figure 1, was specifically developed for industrial applications.

The other major type of cyclic accelerator used by industry is the synchrotron, which produces the highest particle energies (GeV) in that category. A ring of magnets that can be ramped up in field intensity maintains the beam in a circular orbit while it is being accelerated in RF cavities. Electron synchrotrons designed to produce synchrotron radiation for research are also widely used for industrial applications. They are mostly large user facilities, commonly known as “synchrotron light sources,” which incorporate multiple beamlines tailored to the specific needs of researchers and industrial user groups.

Electron and ion beams employed in industry span more than nine orders of magnitude in both particle energy and current—from eV to GeV and from nanoamps to amperes. Correspondingly, beam powers range from microwatts to megawatts.

In fact, the physics, engineering, and technology that go into this diverse range of accelerators have led more than a dozen universities so far to recognize accelerator physics as a separate discipline and offer advanced degrees in the subject. The field has benefited enormously from the development of computer codes that simulate the interaction of

beams with accelerating structures and thus facilitate the design of accelerator components. Because the demand for new accelerators for research and industrial applications has evolved so rapidly in the past two decades, there now appears to be a shortage of qualified experts.⁵

Applications of electron accelerators

The use of energetic electrons in industrial applications covers many modes of electron interactions with matter and electromagnetic fields: ionization, chemical changes, heating, bremsstrahlung, and synchrotron radiation. The most widespread industrial use, electron-beam irradiation, relies on the ionizing interactions of electrons with atoms in the irradiated material to alter its chemical or physical properties. That happens when free radicals—molecular fragments with unpaired electrons—created by the electron beam cause secondary reactions in the bombarded material.

Such processes can be classified as either radiation processing or radiation treatment. Radiation processing can perform polymer grafting and cross-linking and the curing of monomers, oligomers, and epoxy-based composites. Radiation treatment is performed for sterilization of medical products and wastewater, disinfections and preservation of food stuffs, decontamination of chimney and flue gases, and degradation of plastics for use in coatings and inks.

Accelerators for electron-beam irradiation, also known as EB irradiators, were first employed in the 1950s for production of wire coatings. They have since developed into a mature technology used in a wide variety of processes.⁶ There are now more than 1500 dedicated EB-irradiation systems worldwide, many installed in large numbers on mass-production lines, as illustrated in figure 2.

Electron accelerators used in EB irradiator systems include virtually all types, from the single-voltage-gap DC accelerators to high-energy electron linacs and high-power Rhodotrons. The lowest-energy systems (80–300 keV) are usually single-gap DC accelerators used to cure coatings on sheets of material and to cross-link plastic laminates and wire coatings. The material to be treated is typically moved horizontally through the vertical beam traversing the single gap.

Medium-energy irradiators (400 keV–5 MeV) are larger DC systems, such as Cockcroft–Walton accelerators and ICTs, used for cross-linking, curing, and polymerization processes in the rubber and plastics industries. They are also used for sterilizing disposable medical products. High-energy systems (5–10 MeV) such as the Rhodotron and high-energy linacs use 25- to 700-kW scanned electron beams for sterilization, disinfection, wastewater remediation, gemstone color enhancement, and treatment of products whose configurations require deep penetration. They also facilitate the treatment of such thick products by generating x-ray beams.

Industrial EB irradiation accounts for a \$90 billion annual market worldwide. Cross-linking of plastics, elastomers, and polymers is its dominant use. Among its products are heat-resistant cable insulation, heat-shrinkable food-packaging films, polyethylene foams for auto interiors, tire rubber, ink, coatings and adhesives, and hydrogels for wound dressings.

A smaller but well-established category of electron-beam irradiation, called EB processing, utilizes well-defined beams of relatively energetic electrons produced by high-voltage acceleration gaps to very precisely transmit thermal energy into a material. Such controlled heating is employed for precision welding, cutting, drilling, brazing, annealing, glazing, and surface hardening.⁷ It is also used for the precise melting of refractory metals (tungsten or molybdenum, for example) in

industrial furnaces that can incorporate multiple beams with a total power of megawatts. Single beams can have power up to 1 MW.

Typically, a diode or triode electron gun produces a beam of 50- to 300-keV electrons that can then propagate in vacuum or air. Such processing systems are used to fabricate parts for the nuclear, aerospace, automotive, and scientific-equipment industries. The systems employed on production lines are often highly specialized for specific applications. Many of them do EB welding on completely automated production lines.

EB processing is particularly important for automotive production, where such systems are used to make gears and to weld and harden camshafts and tie-rod ends. In EB welding, precise energy deposition makes very deep welds possible, as is depicted in figure 3. Complicated weld patterns can be produced using electromagnetic beam-deflection techniques. In EB drilling, rapid computer-controlled beam deflection allows “on-the-fly” drilling of thousands of holes per second in precise, repeatable patterns.

Secondary radiation

High-energy electron beams are used in industry to generate secondary radiation for materials processing, treatment, and inspection. The secondary radiation can be bremsstrahlung x-rays generated by bombarding metal targets with electrons from high-energy linacs, or it can be synchrotron radiation generated by relativistic electrons circulating in a synchrotron. X rays are used for sterilization and radiographic inspection. Synchrotron radiation is used in an ever-increasing number of processing and inspection techniques.

The largest application of bremsstrahlung is decontamination of food and medical devices. Many disposable medical products are now being sterilized by x rays generated by Rhodotrons and 10-MeV linacs. Although sterilization with x rays is less efficient than directly with electrons, x rays are much more penetrating. Because bremsstrahlung systems don't require radioactive materials, with all their attendant

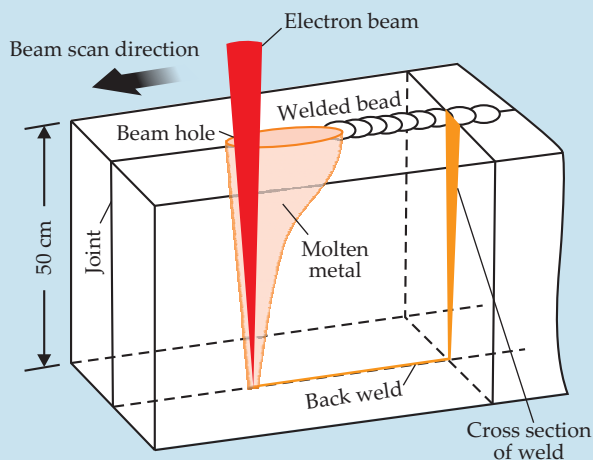


Figure 3. Deep, precision industrial welding of metals is done by high-energy-density electron beams. The beam is scanned along the joint to be welded. When it strikes the metal, the resultant heat instantly vaporizes the metal to form a channel as the beam penetrates into the work piece. Molten material flows around the hole and solidifies to form the weld. The method can produce welds with depth-to-width ratios up to 25:1. (Drawing courtesy of PTR-Precision Technologies, Enfield, CT.)

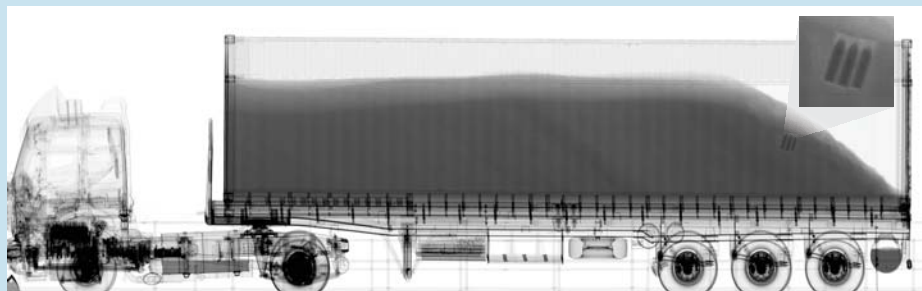


Figure 4. Radiograph of a semitrailer, produced by a 9-MeV electron linac, reveals a case of bottles secreted near the back of a shipment of bulk grain. (Scan courtesy of L-3 Communications and Detection Systems, Woburn, MA.)

concerns, they are overtaking traditional gamma-ray sterilization facilities. Another potentially large application of bremsstrahlung—food and waste irradiation—is thus far still limited, in large part by public fears about the use and effects of radiation.

Radiography is the next largest industrial application of bremsstrahlung. X-ray radiography of large metal castings was one of the earliest applications of electron linacs, because x-ray tubes originally employed for that purpose couldn't generate sufficiently penetrating radiation for thick parts. Linacs with electron energies up to 16 MeV are now widely used for examination of rocket motors and munitions.⁸ The largest industrial application of x-ray radiography is the examination of containers and semitrailers at ports. The technique was originally proposed for security applications, but now it's being employed mostly for customs control (see figure 4).

Synchrotron radiation is nowadays generated at the more than 50 light-source facilities worldwide. The unique properties of synchrotron radiation make it one of the most precise probes of matter available to industry. It has become an indispensable tool for spectroscopic, fluorescence, and x-ray diffraction analysis and for fabrication techniques for the production of microelectronic and microelectromechanical parts.⁹ The miniature motor assembly shown on the cover of this issue was produced by lithographic techniques employing an x-ray beam from a synchrotron light source.

Though most of the industrial work is carried out at synchrotron user facilities, several dedicated systems have been built for industry. Industrial applications include semiconductor-device lithography and the study of material interfaces. The chemical industry uses synchrotron radiation to study reactions and to observe stress and texture patterns in produced materials. Biomedical firms use it for protein crystallography, molecular imaging, and the study of molecular dynamics in tissue cells. Drug development using protein crystallography is by far the largest industrial use of synchrotron radiation.

Using ion accelerators

Industrial applications of ion beams make use of the full range of interactions of ions with materials. They exploit many types of nuclear interactions and the stopping of ions in materials. Ion implantation, primarily into semiconductors, is the largest application of industrial accelerators.¹⁰ It's employed in the fabrication of virtually all integrated circuits and in the cleaving of thin silicon wafers for the production of photovoltaic cells. Almost 10 000 ion-implanter accelerators have been produced over the past half century. The commercial value of the semiconductor components they produce worldwide now exceeds \$250 billion per year.

Those systems accelerate a wide range of ions from hydrogen to antimony, and they must deposit the ions over a

wide range of depths at a uniformity of better than 1%. The range of required ion currents and beam energies has led to the development of a variety of ion accelerators. They can be classified by ion energy and current: High-current implanters employ "accel-decel" techniques to provide variable output energies from 100 eV to tens of keV at currents up to 50 mA. Medium-energy and -current systems use multigap direct-voltage acceleration to energies of 50–300 keV at currents ranging from 0.01 to 2 mA. High-energy, low-current systems produce ion energies of 1–10 MeV at submilliamp currents.

The high-energy accelerators can be either linacs or tandem charge-exchange columns that accelerate high-charge-state ions. For various types of semiconductor doping up to 10^{19} dopant atoms per square centimeter, the required ion energies range from sub-keV to 10 MeV. At a much more modest production level, ions are also implanted into metals to harden cutting tools, reduce friction, and make biomaterials for medical implants. In a few applications, ions are implanted into ceramics and glasses to harden surfaces and modify optical properties.

Nuclear reactions

Ion implantation is usually performed at energies below the Coulomb barrier for most nuclear reactions. But most of the other industrial ion-beam applications actually rely on nuclear reactions. Those applications include many ion-beam analysis techniques; the production of radionuclides for tracers, diagnostic imaging, and cancer therapy; and the generation of neutrons for a number of analytical applications.

Ion-beam analysis techniques originally developed for physics research are now being used in the semiconductor and environmental-monitoring industries to study material properties and monitor contamination levels. Among them are Rutherford backscattering, elastic-recoil-detection analysis, particle-induced x-ray and gamma-ray emission, charged-particle activation analysis, and accelerator-based mass spectrometry.¹¹

Industrial ion-beam analysis is employed for quality-control applications such as contaminant monitoring. Among the R&D applications are geological and oceanographic studies, biomedical science, and renewable-energy development. Even accelerator mass spectrometry, originally developed for radiocarbon dating of tiny samples, has been adapted for environmental monitoring and pharmacology. More than 200 electrostatic accelerator systems, mostly Van de Graaffs, are nowadays used in industry for ion-beam analysis. Some of them are at universities where they were originally used for nuclear physics research but now perform work for industry through contracts and collaborations.

Ion beams are widely used to make radionuclides for medical diagnostic imaging and cancer therapy. More than 50 radionuclide species are routinely produced by light-ion cyclotrons.¹² Among those most widely used for nuclear

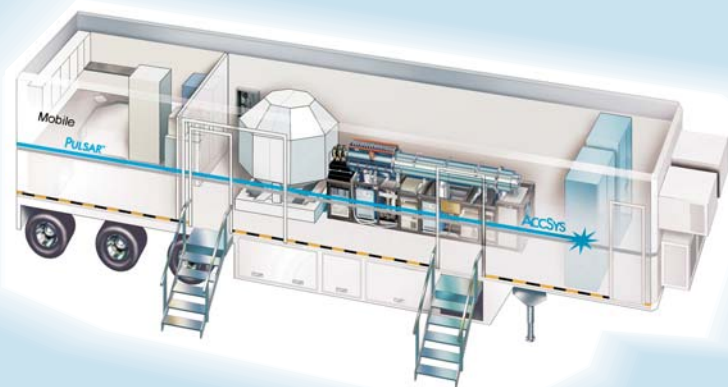


Figure 5. A mobile proton linac system based on an RF-quadrupole accelerating structure creates beams of 7-MeV protons for the production of short-lived radionuclides used in positron-emission tomography. Such mobile units can provide PET radionuclides in remote areas or rapid installation for hospitals and clinics. (Drawing courtesy of AccSys Technology, Pleasanton, CA.)

medicine are fluorine-18 (for PET, positron-emission tomography); iodine-123, thallium-201, gallium-67, and indium-111 (for SPECT, single-photon-emission computerized tomography); and palladium-103 for implantable “seeds” to treat prostate cancer. A few radionuclides are also used in industry for gauging and calibration applications such as thickness and moisture monitoring.

Most of the roughly 650 cyclotrons in operation around the world, plus a few ion linacs, are used at least partially for producing radionuclides. Of those, 350 are dedicated to the production of PET radionuclides. With beam energies ranging from 7 to 19 MeV at currents up to 200 μA , those accelerators don’t need to be housed in shielded vaults. By contrast, most other isotope-production accelerators, with ion energies ranging from 18 to 70 MeV and beam currents up to 2 mA, do require large, shielded facilities.

Although cyclotrons have historically been the accelerators of choice for the large-scale production of radioisotopes, RFQ-based linacs are now being introduced for that purpose. They are smaller and lighter than comparable cyclotrons, and they require less shielding. Such systems may eventually become important if demand increases for the shorter-lived PET-imaging isotopes (carbon-11, nitrogen-13, and oxygen-15) that must be made at or near the point of use. Figure 5, showing a cutaway drawing of a mobile PET-radioisotope production facility, illustrates the versatility of those linacs.

A small but expanding use of ion beams is the production of neutrons for neutron-activation analysis and other analysis techniques in industry.¹³ In the past, many of those applications got their neutrons from radioactive sources. But those sources are increasingly being replaced by accelerators, due in large part to new US regulations imposed in response to security and health concerns associated with the use and storage of radioactive materials.

The majority of accelerator-based “neutron generators” are used for oil and gas exploration and borehole monitoring, mineral detection, and monitoring of various industrial processes. Process monitoring includes on-line analysis of gold, cement, and scrap metal; radiography of manufactured parts; and determination of trace elements in biological and environmental materials. Neutron generators are also increasingly used for nondestructive examinations in the nuclear-waste and homeland-security fields. Security monitors search for concealed high explosives, fissionable materials, and chemical weapons.

The accelerators most often used for neutron applications are small sealed-tube, high-voltage acceleration-gap devices. Of course, they accelerate only charged ions. Accelerated deuterons produce the neutrons by initiating fusion reactions in a deuterium or tritium target. Sealed-tube gen-

erators produce fluxes ranging from 10^6 to 10^{11} neutrons per second and normally operate at voltages from 80 to 225 kV. RFQ deuteron and proton linacs have been commercially developed in recent years for applications requiring higher neutron yields or specific beam characteristics not achievable with sealed tubes. They can produce as many as 10^{13} neutrons per second.

Manufacturing accelerators

The widespread adoption of accelerators in industry in recent decades has resulted in an escalating growth of the business of making them. Manufacturing of industrial accelerators is now a worldwide business carried out by more than 65 companies and institutes. Most of them are in North America, western Europe, and Japan, but a growing number are in Russia, India, and China. The majority of industrial accelerators nowadays are produced by only a few large vendors, but smaller vendors do serve particular geographic regions and niche markets.

The number of new vendors is increasing as accelerator technology is adopted by growing industries in emerging economies. Collectively, industrial accelerator producers ship almost 1000 systems per year, with a sales value exceeding \$2 billion worldwide. The range of applications will surely expand, and the technology will evolve, because users are continuously seeking lower total cost and better return on their capital investment.¹⁴

Several technologies currently approaching initial acceptance for industrial applications include the free-electron laser (FEL), superconducting cyclotrons and linacs, and the new fixed-field alternating-gradient (FFAG) rings. The FEL is the next generation of smaller and cheaper synchrotron light sources that could be used for many applications now performed at the big synchrotrons. New superconducting cyclotron and linac structures will result in increased efficiency and smaller size once the related cryogenic technology becomes cheaper and more reliable. FFAG accelerators achieve the cyclotron’s advantage of continuous, unpulsed operation with the synchrotron’s ring of smaller, narrow-bore magnets. The concept, first proposed in 1954, is currently being developed for high-energy physics research. But it is also being developed as a neutron source for medical use.

The list of products containing materials and parts that have been touched in some way by a charged-particle beam is long and impressive. Our conservative estimate is that the commercial value of those parts now exceeds \$500 billion per annum worldwide. As advances are made in existing accelerator technology and as new technologies mature into commercial products, the applications of industrial accelerators will undoubtedly continue to grow. Most accelerator manufacturers and industrial users are busy even now working on

new uses and markets, but much of that effort is heavily guarded for competitive reasons.

We gratefully acknowledge the important contributions made by the writers of the chapters in the upcoming book, *Industrial Accelerators and Their Applications*, being edited by us. Many of the details included in this article are summarized from their work. The book is expected to be published by World Scientific later this year.

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Wide-Band CURRENT MONITORS

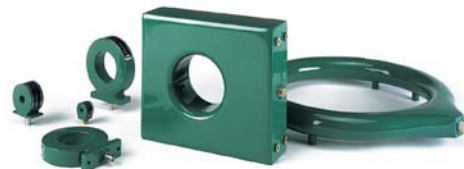
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