

INDUSTRIAL ACCELERATORS

Robert W. Hamm and Marianne E. Hamm
R & M Technical Enterprises, Inc., Pleasanton, CA 94566, USA

Abstract

Particle accelerators were originally developed for basic science research but are increasingly being employed for industrial applications. Industrial accelerators are now produced by more than 70 institutes and commercial companies around the world that collectively ship more than 1000 systems per year. The applications of these accelerators can be categorized into a broad range of industrial business segments ranging from low energy electron beam systems for welding, machining, and product irradiation to high energy cyclotrons and synchrotrons that produce radioisotopes or synchrotron radiation. This paper reviews the various business segments, the applications of accelerators within them, and their impact on our lives and the economy. It also discusses the future growth of existing applications as well as new technology under development that will likely be used in future industrial applications.

INTRODUCTION

While the use of particle accelerators for treating cancer is well known, their use in most industrial applications is not common knowledge. In this paper, we define “industrial accelerators” as all charged particle devices that generate external beams for any beam process other than direct medical treatment or basic physics research [1]. Cathode ray tubes, X-ray tubes, radio frequency and microwave power tubes, and electron microscopes that use internal particle beams are not included, even though they are all produced by industry. Two specialized industrial accelerator applications are also not included: focused ion beams (FIB) used in the semiconductor industry for the inspection and ablation of materials, and ion beam figuring (IBF), a relatively new technique used in preparing optical and nano-material surfaces. However, we do consider the accelerator production of radionuclides for medical diagnostics and treatment of disease to be an industrial application, as most are produced by for-profit businesses using accelerators built by industry for these markets.

Industrial accelerators utilize essentially all of the acceleration methods originally developed for research as well as some that were developed specifically for industry. These include electrostatic systems, RF linacs, betatrons, cyclotrons, Rhodotrons, and synchrotrons. As can be seen from Fig. 1, which shows the typical beam parameters for many industrial applications, the electron and ion beams produced by these devices span more than nine orders of magnitude in particle energy and current: from eV to GeV and from nano-amperes to amperes. Output beam powers vary from a few microwatts to more than a megawatt.

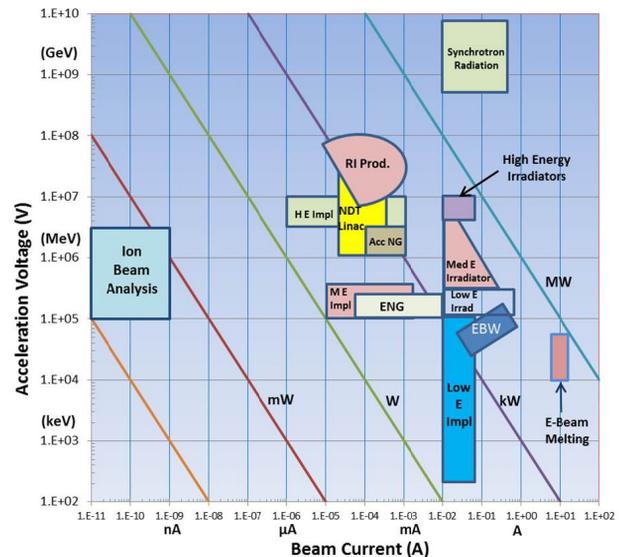


Figure 1: Range of industrial accelerator parameters.

Over the past 60 years, more than 27,000 charged particle beam accelerators have been built worldwide for use in industrial processes [2]. This total does not include the ~14,000 accelerators that have been produced for medical therapy with electrons, ions, and X-rays. Figure 2 shows an updated breakdown by broad industrial application categories covered in Ref. 2.

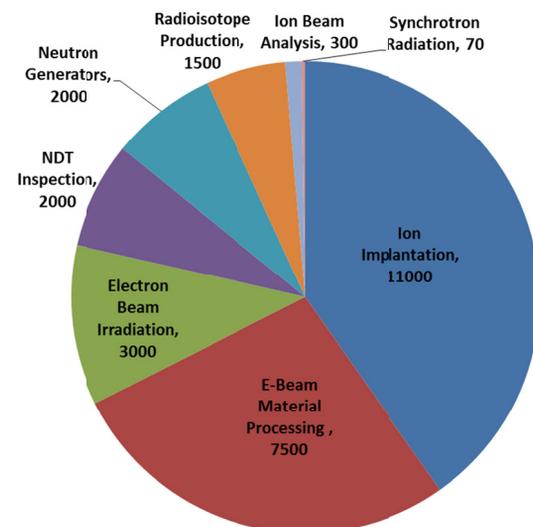


Figure 2: Updated estimates of systems built to date for a number of established industrial accelerator applications.

Since the average life for most industrial accelerators is 20–40 years, at least 75% are still in operation today. Even though the technology has changed slowly over the years, the adoption rate as industrial processing tools has

steadily increased. This in turn has driven the growth of the accelerator manufacturing business in order to meet the demand.

HISTORICAL DEVELOPMENT

As has been described by Sessler and Wilson [3], most modern industrial accelerator technology was originally developed in the 1930s for physics research. The history of these devices shows that soon after a new type of accelerator was invented someone recognized its potential for practical applications, often as a result of basic research on the interactions of the energetic output beams with matter for the measurements of cross-sections and material properties. However, while the practical uses of a new type of accelerator were often explored soon after its invention, it often took decades before it gained widespread acceptance and use as an industrial tool. A leading example of this is ion implantation in semiconductors, which is today the largest application of accelerators in industry. William Shockley proposed this process in the 1950s, but the fledgling industry to build systems did not materialize until a decade later and ion implantation did not become a widely accepted industrial technique for another decade [4].

This long acceptance cycle in the “beam business” is due to the users (customers) being most concerned with the cost-effectiveness and reliability of employing an accelerator in their manufacturing or production process. To them the accelerator is a “black box”. This means that before a system can be widely accepted by industry it must first be developed into a device with repeatable output and then demonstrated in an industrial setting for several years to prove its viability as a reliable tool.

Most industrial applications evolved from basic or applied science programs through the use of research accelerators to develop an industrial process, but these research systems are usually not capable of handling the throughput and reliability of routine use in a factory environment. As a result, the performance requirements demanded by industry have led to significant advances in accelerator technology, and the accelerators developed for industrial use have evolved into high quality products often tailored to a specific application.

STATUS OF THE “BEAM BUSINESS”

As mentioned above, the widespread adoption of accelerators as industrial processing tools has resulted in the robust growth of the global accelerator manufacturing business. In this high-tech, capital-intensive business, the names and numbers of the players are continuously changing. New companies appear with the development of a new technology or application, while others get acquired by competitors or other businesses in their application area. Not many simply go out of business. Most industrial accelerators are currently produced by a few large vendors in North America, Europe, and Japan, but the number of vendors in Russia, India, Korea, and China is growing. Most new vendors initially limit sales

to their particular geographic region or niche markets, while the number of vendors will rapidly increase as the technology is widely adopted in a given geographical region or market. However, as a particular application matures, some vendors will grow in size but their numbers will dwindle due to competition.

Collectively, industrial accelerator producers ship more than 1000 industrial systems per year with annual revenues exceeding US\$2B [2]. As of 2008, the growth in sales was estimated to be almost 10% per year, although this has undoubtedly slipped due to the recent economic recession experienced by most developed countries where these systems are built and deployed.

The industrial accelerator market is expected to continue growing as the number of applications and markets expand. The technology used will also evolve because the initial capital cost, operating cost, and reliability of an accelerator system plays an important role in these “for-profit” industrial applications. Hence, industrial users will seek ways to increase their return on investment, which can in turn push the development of new or improved accelerators by the manufacturers.

ESTABLISHED APPLICATIONS

Both electron accelerators and ion accelerators are utilized in industrial applications, with the specific type used for a given application being determined by both the required characteristics of the output beam and the physics or chemistry involved in the process [5]. In this section we briefly describe the established industrial applications and the types of systems employed.

Electron Accelerator Applications

The most wide-spread use of electron beams by industry is commonly referred to as “electron beam irradiation”. This application relies on the ionizing interactions of electrons with atoms in irradiated materials to alter their chemical and/or bulk physical properties. This occurs when the free radicals created by the electrons (ions and slow electrons) cause secondary reactions in the bombarded material. These processes can be described as either radiation processing or radiation treatment [6]. Radiation processing includes polymer grafting and cross-linking, and curing of monomers, oligomers and epoxy-based composites. Radiation treatment includes sterilization of medical products and waste water, and irradiation of food and feed products for disinfestations and preservation. It also includes the irradiation of flue gases to remove atmospheric contaminants, and the decomposition of plastics for use in coating and inks.

More than 2000 dedicated electron beam irradiation systems are currently in use worldwide, with large numbers of them installed in factory production lines. These electron accelerators include virtually all types from the simple single-voltage-gap dc accelerators to high energy electron linacs to the high power Rhodotron. They can be divided into three categories by output energy:

- Low energy systems (80–300 keV) are typically single-gap dc “line” beam accelerators (i.e. the material is moved through the horizontal plane of the stationary beam). They are used to cure coatings on sheets of material and to cross link plastic laminates and single strand wire coatings.
- Medium energy irradiators (400 keV to 5 MeV) are larger dc systems such as Dynamitrons, Cockcroft-Waltons, and ICTs. These are used for cross linking, curing, and polymerization processes in the tire, rubber, and plastics industry.
- High energy systems (5–10 MeV), such as the Rhodotron and high energy electron linacs, use 25–700 kW scanned electron beams for sterilization of medical products, irradiation of food for preservation and disinfestation, waste water remediation, gemstone color enhancement, and cross linking and polymerization of thick cross section products.

The market served by industrial electron beam irradiators has an annual value of more than US\$50B. The largest use is for cross linking of materials. Typical products include [7]:

- Heat resistant wire & cable insulation.
- Heat-shrink tubing.
- Heat shrinkable food packaging films.
- Closed cell polyethylene foams for auto interiors & medical parts.
- Tire rubber components.
- Inks, coatings, and adhesives cured on paper, wood, metals, and plastics.
- Hydrogels for wound dressings.

The oldest category of electron beam applications is “EB processing”, in which a well-defined beam of relatively energetic electrons produced by a high voltage gap is used to transmit thermal energy into a material in a precise manner [8]. This controlled deposition of heat is used for precision welding, cutting, and drilling of materials, as well as brazing, annealing, glazing and surface hardening. This precise energy deposition can produce very deep welds and makes it possible to weld dissimilar metals. It is also used for the precise melting of many refractory metals in furnaces that can have multiple electron beams with a total power of several MW.

There are ~4000 EB processing systems now in operation worldwide (~1000 in the US), the majority of these being EB welders. Because of their reliability and precision repeatability, many are used in completely automated production lines. EB processing is a critically important technique in automotive production, where it is used to produce speed gears and to weld and harden parts (such as camshafts and tie-rod ends).

In the remaining category of electron accelerator applications, fast electrons are used to generate secondary radiation for materials processing, treatment, and inspection. This secondary radiation is either in the form of X-rays (bremsstrahlung) generated by bombarding heavy metal targets with high energy electrons, or coherent light (synchrotron radiation) generated by

relativistic electrons moving in the circular path of a synchrotron.

Decontamination of medical devices and food packaging with bremsstrahlung is the largest application in this category, with many disposable medical products now being sterilized using X-rays generated by Rhodotrons and 5–10 MeV electron linacs. Although sterilization with X-rays is less efficient than with direct electron beams, X-rays penetrate deeper into the material making it possible to sterilize thicker packages. These systems are beginning to overtake the traditional gamma-ray sterilization facilities due to concerns of safety and shortages of the large radioactive sources required. Another potentially large application in this area is food and waste irradiation, although these have yet to gain widespread acceptance in many countries due in large part to public fears concerning the effects of radiation.

Radiography is another large application of secondary radiation. X-ray radiography of large castings was one of the earliest applications of electron linacs because the conventional X-ray tubes originally employed for this purpose were not able to penetrate through thick parts. While the earliest systems were electron accelerators developed for X-ray cancer therapy that had been modified for industrial use, modern versions are specifically designed for industrial use. Electron linacs with energies of 1–16 MeV are now widely used for examination of rocket motors and munitions, including industrial CT examination systems [9]. The largest X-ray radiography application is for port examination of containers and semi-trailers — an application originally proposed for security but now also being employed for import/export control.

The final “tool” used in the secondary radiation category is the synchrotron radiation (SR) generated at more than 50 Synchrotron Light Source (SLS) facilities located around the world. Almost all industrial work in this field is being conducted at user facilities, although a few dedicated systems have been built specifically for industry. The unique properties of synchrotron radiation make it one of the most precise probes of matter possible, and it has become an indispensable tool used in many industries [10]. Industrial uses of SR include X-ray diffraction, spectroscopy, and fluorescence examination, as well as several fabrication techniques for the production of micro-electromechanical system (MEMS) and microelectronic parts.

Industrial applications include lithography, studies of material interfaces, and other production issues in the semiconductor industry. The chemical industry uses SR to study such properties as stress or texture of various materials produced, as well as the chemical reactions themselves. The biomedical industry utilizes SR for drug and biomaterial development through protein crystallography, molecular structure imaging, and molecular dynamics studies in tissue cells. In fact, drug development using protein crystallography is by far the largest industrial use of SR by industry. Nearly every SLS has at least one user beamline dedicated to this technique.

Ion Accelerator Applications

The industrial applications of ion accelerators include ion implantation, ion beam analysis (IBA), radionuclide production, and generation of neutrons. The largest industrial application of ion beams is ion implantation, primarily in semiconductor materials for the production of modern electronic integrated circuits [11]. This technique includes fabrication of CMOS transistors for IC devices, fabrication of CCD & CMOS imaging chips for cell phones and digital cameras, and cleaving of thin silicon wafers for the production of photovoltaic solar cells. A typical IC undergoes 25 to 30 implants during fabrication.

Ion implantation systems accelerate a wide range of ions from hydrogen to antimony and must deposit them over a wide range of depths at a uniformity of better than 1%. The wide range of accelerator parameters required in this application is shown in Fig. 3, which plots the projectile energy versus integrated ion dose for a number of specific semiconductor implantation techniques. The sale of commercial accelerators for ion implantation is currently estimated to be a US\$1B per year business, with the commercial value of the semiconductor components produced exceeding US\$250B per year. This does not even count the market value of the enormous number of electronic products in which the components are used.

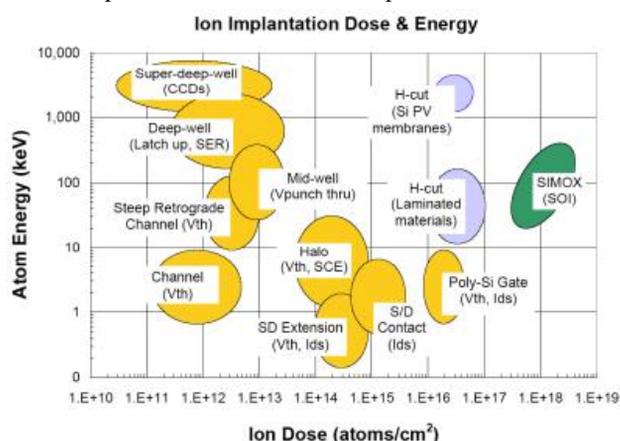


Figure 3: Ion dose and atom energy for various types of semiconductor devices [11].

Ion implantation is usually performed at energies below the Coulomb barrier for most nuclear reactions, but most of the other industrial ion beam applications rely on nuclear reactions occurring. These include most of the analysis techniques used in the field of Ion Beam Analysis (IBA), the production of radionuclides for tracers, diagnostic imaging, and cancer therapy, and the production of neutrons for many analytical applications.

While IBA of materials is today still a large area of physics research, the techniques developed in this field are being utilized in the semiconductor and environmental monitoring industries for studies of material properties (profiling) and for determination of contamination levels. The techniques used were adapted from methods developed for experimental nuclear physics and include:

- Rutherford Back Scattering (RBS).
- Elastic Recoil Detection Analysis (ERDA).
- Particle Induced X-ray Emission (PIXE).
- Particle Induced Gamma Ray Emission (PIGE).
- Nuclear Reaction Analysis (NRA).
- Charged Particle Activation Analysis (CPAA).
- Accelerator Mass Spectrometry (AMS).

Industrial IBA is mainly employed for Quality Control and R&D, such as contaminant monitoring, environmental monitoring, geological and oceanography studies, biomedical science, and renewable energy development. Even AMS, originally developed for radiocarbon dating, has been adapted for environmental monitoring and pharmaceutical development. It is estimated that there are more than 200 electrostatic accelerator systems, most of them tandem Van de Graaffs, being used by industry for IBA. A number of these are at universities where they were originally purchased many years ago for low energy nuclear physics research and are now being used to do work for industry through contracts and collaborations.

Another wide-spread application of ion beams is the production of radionuclides for use in medical diagnostic imaging and in the treatment of tumors and diseases. More than 50 radionuclides are routinely produced by accelerators (mostly light-ion cyclotrons), and the number is growing as more biological applications are discovered [12]. The radionuclides most widely used for nuclear medicine include: ^{123}I , ^{201}Tl , ^{67}Ga & ^{111}In for Single Photon Emission CT (SPECT); ^{18}F for Positron Emission Tomography (PET); and ^{103}Pd for the implantable “seeds” used extensively to treat prostate cancer. Although on a much smaller scale, a few of these radionuclides are also used in industry for gauging & calibration, including thickness monitoring and moisture determination. The value of the commercial production of radionuclides and the radiopharmaceuticals in which they are used is more than US\$600M annually, with most of the ~650 cyclotrons in operation around the world plus a few ion linacs being used at least partially for this purpose. Of those, 350 are dedicated to the production of PET radionuclides.

A smaller but expanding use of ion beams is for the production of neutrons for a host of analysis applications in industry [13]. In the past, many of these applications used neutrons from radioactive sources such as ^{252}Cf and $^{241}\text{AmBe}$. However, radioisotope sources are increasingly being replaced by “electrically driven” accelerators due in large part to new US regulations imposed in response to growing environmental, security, and health and safety concerns associated with their use and storage. The majority of these “neutron generators” are used in the oil and gas exploration industry for oil well logging, for mineral detection in the mining industry, and for industrial process monitoring. Oil well logging is by far the largest application. Industrial process monitoring includes: (1) on-line bulk material analysis of gold, coal, cement, and scrap metal; (2) radiography and gauging of parts such as munitions; and (3) the determination of trace

elements in biological and environmental materials by neutron activation analysis. Neutron generators are also used on a smaller but increasing scale for non-destructive examinations in the nuclear waste, safeguards, and homeland security fields. This includes the detection of contraband, high explosives, fissionable materials, and chemical weapons agents. The accelerators most used for neutron applications are small sealed-tube, high-voltage acceleration gap devices utilizing the DD and DT fusion reactions. Sealed-tube neutron generators produce fluxes ranging from 10^6 to 10^{11} n/s and normally operate at voltages from 80 to 225 kV. RFQ linacs have been commercially developed and sold in recent years for applications requiring higher neutron yields and/or specific beam characteristics not achievable with sealed tubes. These are proton or deuteron systems with output energies from 1 to 4 MeV and beam currents up to 1 mA. They can produce neutron yields of 10^8 to 10^{13} n/s depending on the beam and target combination.

FUTURE DEVELOPMENTS

As the industrial uses of accelerators continue to expand, there will be more demand for advances in the technology to improve both performance and capability. These challenges will fall mainly in two areas:

- Improvements in the beam intensity and reliability of accelerators, particularly those useful for energy and environmental applications.
- Improvements in the capability and performance of the accelerating structures to make them more robust, efficient, and compact.

As described earlier in this paper, new accelerator technology is usually first developed and proven for research applications at national laboratories and universities using government funding before being adopted by industry [14]. Although we do not have a crystal ball to see into the future, we feel that there are several research systems that are approaching initial acceptance for industrial applications. These are the compact synchrotron light sources, superconducting cyclotrons and linacs, and the new fixed-field alternating-gradient ring (FFAG). The Free Electron Laser (FEL) and the Laser Electron Light Source, which employs inverse Compton scattering, are the next generation of smaller and cheaper synchrotron light sources that could be used for many applications now performed at the present much larger SLS facilities. Similarly, new superconducting cyclotron and linac structures will result in an increase in efficiency and a reduction in the size of these accelerators — once the related cryogenic technology becomes more proven and less costly through its widespread use in large research and medical accelerators. Large applications requiring high current systems will not be commercially feasible until these technologies provide more power efficient accelerators [15]. The FFAG concept has actually been around for many years, having first been proposed in 1954, and is currently being developed for high energy physics research at several national

laboratories. However, it is also being developed for medical applications [16]. If it proves to be useful in those applications, it will quickly be adapted for industrial applications with neutron beams.

As new technologies are developed into commercial products, the uses and applications of industrial accelerators will continue to grow. There is no doubt in our minds that most accelerator manufacturers and industrial users are continually working on new markets and uses, but they are understandably reluctant to publicize their R&D efforts in order to maintain a competitive advantage.

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