# Review of Industrial Accelerators and Their Applications

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**Abstract.** Of the particle accelerators that have been manufactured by for-profit entities worldwide, about half are used for industrial applications. These industrial systems utilize a wide range of accelerator technologies, including direct voltage systems, rf and microwave linacs, and cyclic accelerators. They accelerate either electrons or ions with energies and currents spanning more than six orders of magnitude. Their numerous applications cover a broad range of business segments from low energy electron beam systems for welding, machining, and product irradiation to high energy cyclotrons and synchrotrons for medical isotope production and synchrotron radiation production. Although industrial accelerator manufacturing is not a high profile business, these systems have a significant impact on people's lives and the world's economy, as so many commonly-used materials and products, both durable and consumable, are processed by charged particle beams. Wide scale industrial use of many of these processing tools has resulted in the rapid growth of the industrial accelerator business. This paper is a review of the current status of this business worldwide, including the technologies, the applications, the vendors and the market sizes.

## 1. Introduction

Most (> 99%) of the particle accelerators produced worldwide are used for commercial applications, half for medical treatment and half for industrial applications. Medical accelerators treat cancer and other diseases in millions of people each year, while industrial accelerators are used for processing numerous products with charged particle beams and for doing analysis on many others. Since medical accelerators have been thoroughly reviewed [1], this paper will cover only industrial accelerators. These include all accelerators that generate external beams for use in a beam process other than medical treatment or physics research. Those devices that use low energy charged particles internally, such as cathode ray tubes, x-ray tubes, radio frequency and microwave tubes and electron microscopes, are not included. The description of the accelerators and applications will necessarily be brief, but more details are available in a recently published in-depth review by the author [2].

## 2. Types of Industrial Accelerators

The different charged particle accelerators currently used for industrial applications are listed in Table I by the acceleration techniques employed. As described by Sessler and Wilson [3], the technology for most of these accelerators was developed in the 1930's for physics research. However, the stringent performance requirements demanded of most modern industrial accelerators have led to tremendous advances in the technology.

TABLE I: CURRENT INDUSTRIAL ACCELERATORS

| **Direct Voltage Accelerators** | **RF Linear Accelerators** | **Cyclic Accelerators** |
|---|---|---|
| Van de Graaff | Coupled Cavity Linac | Cyclotron |
| Dynamitron | Radio Frequency Quadrupole | Betatron |
| Cockcroft Walton | Drift Tube Linac | Rhodotron |
| Inductive Core Transformer | | Synchrotron |

Direct voltage accelerators use electrostatic voltages produced by a high voltage power supply to accelerate electrons or ions. Voltage generation methods include electrostatic charging using a charge carrying belt or “chain”, a voltage multiplier circuit, or a step-up transformer. For most high energy systems (voltage >300 kV) the high voltage supply is an integral part of the accelerator, but for lower voltages it is externally connected through a high voltage cable.

RF linear accelerators use radio frequency (rf) generated voltage to accelerate electrons or ions in bunches that are synchronized with the rf frequency. While most electron linacs use a side-coupled cavity and operate at rf frequencies from 800 MHz (L-band) to 9 GHz (X-band), all modern industrial ion linacs use the Radio Frequency Quadrupole (RFQ) as the first (or only) accelerating structure and operate at rf frequencies from 100 to 600 MHz.

Cyclic accelerators use magnetic fields to constrain an electron or ion beam to a spiral or circular path while accelerating them with rf voltages. The cyclotron is the oldest and most commonly used accelerator of this type for ion beams, but is impractical for electrons due to relativistic effects. Advances in technology have resulted in modern industrial cyclotrons achieving higher currents than their predecessors by accelerating negative ions for better beam extraction and using large-gap, strong focusing magnets to minimize beam loss.

The betatron is the next oldest technology in the cyclic category. It was developed just to accelerate electrons and uses only a changing magnetic field (no rf). Many betatrons were built in the last century for non-destructive testing and medical applications, but the modern compact electron linac structure made them less practical so they only have limited industrial use today in high energy x-ray inspection. The Rhodotron$^{TM}$ is a new cyclic industrial accelerator also developed specifically for electrons. It uses a coaxial resonator to accelerate electrons with 1 MeV per pass. Magnets placed around the circumference of the cavity allow multiple passes through the cavity to produce high energies.

Synchrotrons produce the highest energy beams (GeV) of the cyclic accelerators. A ring of magnets with a changing magnetic field maintains an injected beam of electrons or ions in a constant radius orbit as it is accelerated in an rf cavity by tracking the frequency of the rf voltage. Electron synchrotrons built to produce synchrotron radiation for research are also used for industrial applications, while ion synchrotrons are mostly used for cancer therapy.

## 3. Industrial Accelerator Applications

Soon after particle accelerators were invented, it was recognized that they could be used for practical applications as a direct result of the research being done on the interaction of particle beams with materials and measurements of material properties. The present-day industrial applications that developed can be divided into the broad categories described below.

### 3.1 Ion Implantation

Ion implantation is by far the largest industrial application of accelerators (mainly direct voltage systems), and the semiconductor industry is by far the largest user. Figure 1 is a plot of the various ion implantation semiconductor applications as a function of the ion energy and implanted dose of ions required [4]. These include the use of accelerated ions from protons to antimony at beam energies from hundreds of electron volts to almost 10 MeV. While the most common application is the doping of silicon for production of semiconductor devices, Fig. 1 also illustrates several other important applications in the field. These include “mesotaxy”, a technique of matching an implanted ion layer within a crystalline material, and the fabrication of “silicon on insulator” (SOI) substrates used in electronic, photonic and micro-electronic mechanical systems (MEMS) devices.

Ion implantation is also widely used to modify the surface properties (hardness, stress, adhesion, friction, dielectric, and corrosion and chemical resistance) of metals, ceramics and glasses without changing the bulk properties. Common uses for metals include cutting tools and artificial human joints that last longer after ion implantation. For ceramics and glasses, ion implantation can change their optical properties and make them stronger.

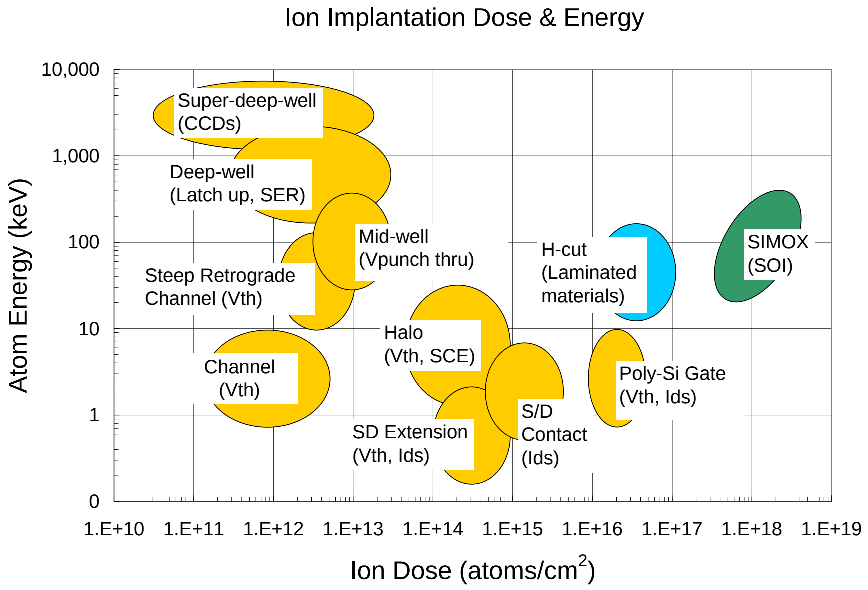

*FIG. 1. Ion energy and implanted dose ranges for various semiconductor applications.*

## 3.2 Electron Beam Processing

Industrial processing with electron beams is almost as large an accelerator application as ion implantation. Processing applications fall into two broad categories: (1) modifications of materials (welding, melting, cutting, drilling and hardening) and (2) irradiation, which includes radiation processing of polymers, monomers, oligomers and epoxy based composites, food preservation, product sterilization and waste treatment.

### 3.2.1 Electron Beam Modification

In most electron-beam modification systems, electrons from an electron gun are accelerated to energies in the range of 60 to 200 keV using a triode electrostatic gap. The electron beam is then used to precisely machine, cut or weld work pieces in a vacuum chamber attached to the gun. An electromagnetic lens focuses the beam onto the work piece, and a magnetic deflection system locates and moves the beam. Some systems even allow the processing of larger pieces at atmospheric pressure by passing the beam through a thin vacuum window. Since electron penetration in materials is proportional to the energy, it is possible to weld much thicker pieces with high energy electrons than in conventional welding processes. Since the electron beam is tightly focused on the object, the total heat input is also much lower than that of conventional welding. Objects cool quickly, allowing many dissimilar metals to be welded. Almost all metals can be processed, the most common being super alloys, refractory or reactive metals, and stainless steels. Ceramics and other materials can also be processed.

### 3.2.2 Electron Beam Irradiation

Bombarding a material with energetic electrons can promote chemical processes by generating ions and slow electrons which modify the material's atomic bonds through interactions with the free radicals. This can alter both its chemical and physical properties. Applications of such radiation processing are numerous and varied in nature but can be divided into four main categories: curing and drying of coatings and materials; production of cross-linked, scissored and grafted polymers; sterilization and food preservation; and waste water and gas treatment. There are other applications such as curing composites, viscose production, and thermo-mechanical pulp production that have been demonstrated but are not yet in wide-spread use.

The electron beam energy required for the uniform dose needed in these applications is determined by the thickness and density of the material being processed. The accelerators hence cover a wide range of beam energies and can be classified as low (<300 keV), medium (300 to 1000 keV) and high (1 to 10 MeV) energy systems. Low energy systems are used for curing thin film coatings on sheet material and for cross-linking plastic laminates and single strand wire. Medium energy systems are mainly used for cross-linking, polymerization and curing in the tire, rubber and plastics industries. Output beam currents can range from 10 to 250 mA and strips of material up to as wide as 3 meters can be processed.

High energy systems are used for cross-linking and polymerization of thicker materials, and for sterilization of medical products. They are also used with a water-cooled tungsten target to generate high energy x-rays for food irradiation, waste water remediation, and gemstone color enhancement, particularly topaz and diamonds. The maximum energy is 10 MeV to avoid activation of the bombarded materials from nuclear reactions that occur above that energy; however food irradiation has been approved by the U.S. FDA only up to 7.5 MeV [5].

The cross-linking of polymers is the largest industrial application of electron beam irradiation. The largest uses are in the wire and cable industry, the heat shrink film and tube industry and the tire industry, with the commercial value of these products exceeding $50 billion per year [6]. The next largest application is the sterilization of single-use disposable medical products and supplies such as surgical gowns, surgical gloves, syringes and sutures. In fact, medical products with a sales value in excess of $10 billion/year are sterilized using electron beam irradiators [7]. In addition, pharmaceutical companies are using electron beam irradiation for sterilizing drug ingredients.

### 3.3 Ion Beam Analysis

The use of ion beams for analysis of materials is a relatively new industrial application of electrostatic accelerators (mainly Van de Graaff systems) used in many fields ranging from materials and environmental sciences to the study of cultural heritage and biological samples. The precise energy resolution of the ion beams make these systems ideal tools for using one of many well-established analytical analysis methods (such as Rutherford Back Scattering, Particle Induced X-ray Emission or Charged Particle Activation Analysis) along with the vast data base of known reactions and cross sections to determine the properties of a given material as well as the presence, quantity and distribution of trace elements or contaminants. The biggest industrial uses of ion beam analysis are in the semiconductor industry for quality control and environmental sciences for pollution monitoring.

A newer ion beam analysis technique is accelerator mass spectrometry (AMS). This differs from conventional ion beam analysis in that a small sample of the material to be analyzed is itself ionized to form the beam. AMS uses the mass and charge-differentiation capability of an accelerator with a specially designed beam line to measure long-lived radioisotopes such as $^{14}C$ as markers or environmental and biomedical tracers with sensitivities as high as 1 part in $10^{15}$. Industrial applications of AMS include uses in the applied fields of oceanography, geology and biomedical science. The fastest growing use of AMS is in the development of drugs where the high sensitivity of the technique permits the use of "micro-dosing" for the determination of the pharmacokinetics of new drugs.

### 3.4 Radioisotope Production

Not long after the first cyclotrons were developed in the 1930's for physics research, they were used to produce radioisotopes. In the 1960's several companies began selling small cyclotrons dedicated to radioisotope production. Even though proton linacs at the high energy physics research facilities have also been used to produce radioisotopes, ion linacs were too large and expensive to be practical for commercial systems until the RFQ accelerating structure and compact ion source were developed at Los Alamos in the late 1970's.

The largest commercial use of radioisotopes is in the diagnosis of cancer and other diseases. While the most widely used isotope, $^{99}Mo$, can only be economically produced in a nuclear reactor, more than 10 million diagnostic procedures are now performed every year using over 50 radioisotopes routinely produced by accelerators ranging in energy from 7 to 70 MeV [8]. These include the most common traditional gamma-ray emitters (such as $^{201}Th$, $^{67}Ga$, $^{123}I$, $^{111}In$ and $^{103}Pd$) and the short-lived positron emission tomography (PET) isotopes ($^{11}C$, $^{13}N$, $^{15}O$ and $^{18}F$). While the majority of radioisotopes are used for single photon emission computed tomography (SPECT) and PET, their use in other applications such as measuring flow, determining moisture and thickness, and mutating plants is increasing.

Most accelerators sold for radioisotope production are 10 to 30 MeV proton cyclotrons, but commercially-available linacs are becoming more competitive. The largest market is for smaller dedicated PET systems. These short–lived isotopes must be produced in close proximity to the user's site (i.e. 2 hour delivery radius for $^{18}F$). The market demand, which is large and still growing, has spurred the continued development of compact accelerators (both linacs and cyclotrons), with more than 400 systems now in use worldwide.

### 3.5 High Energy X-Ray Inspection

Electron linacs in the energy range from 1 to 16 MeV are widely used for non-destructive inspection applications. Penetrating high energy x-rays generated by bombarding a tungsten target have been used for almost 50 years to locate flaws in large metal castings and welded joints as well as to inspect large solid-fuel rocket motors. Because the parts being inspected are often very large and heavy, early commercial units were designed to be mobile so they could be moved around the part. With the advent of real-time detection technology, high energy x-ray inspection systems were developed to incorporate computed tomography imaging techniques. Also, the in-situ inspection of parts in fixed installations, such as in nuclear power plants and bridges, has led to the development of very compact portable systems [9]. These employ 9 GHz resonant cavity structures instead of the 3 GHz microwave structures used in conventional electron linacs designed for this application.

A newer, much larger application of high energy electron linacs is the inspection of large cargo containers and semi-trailers at border entry points. Originally deployed to stop the entry of weapons and illicit materials, these systems are now also being used for cargo screening to collect duties and taxes on improperly declared shipments. First deployed at the Eurotunnel between Europe and the UK [10] in 1983 for security, the worldwide market demand for these cargo inspection systems is growing rapidly. Border inspection systems are now deployed in more than 20 countries. These new systems are self-shielded and emit a collimated fan beam that passes through the cargo. A line detector on the opposite side produces a radiograph of the cargo container's or vehicle's contents. The latest innovation is the use of simultaneous dual energy beams that allow the differentiation of heavy elements, such as uranium or lead.

### 3.6 Neutron Generators

While the majority of industrial applications of neutrons still utilize nuclear reactors or radioisotope sources, accelerator-based neutron generators are becoming more widely used due to their mobility and ability to be turned off. The most commonly used neutron generator is the classic electrostatic "sealed tube" system which produces mono-energetic fast neutrons via the $D(d,n)^3He$ or the $T(d,n)^4He$ reaction. Sealed tube generators are used extensively in mineral analysis and oil-well logging applications.

Larger accelerator systems (electrostatic tandems, cyclotrons and linacs) that generate neutrons via a variety of induced nuclear reactions are also used in industry [11]. When coupled with a suitable moderator, they replace conventional radioactive sources in thermal neutron radiography applications ranging from corrosion detection in aircraft structures to detection of voids in munitions. They have been used for fast neutron and resonant neutron radiography, since energetic neutrons can penetrate thick materials and detect hidden features. Even though several systems have been developed and demonstrated for diverse non-destructive testing applications ranging from mineral assay to homeland security, the market remains small. However, new security applications could drastically increase the demand.

### 3.7 Synchrotron Radiation

Soon after the discovery of synchrotron radiation from the 300 MeV electron accelerator at General Electric, high energy synchrotrons built for physics research were used as sources of intense x-rays for materials studies. While there are only a few of these large accelerators in industrial settings, more than 40 systems installed worldwide in research centers are being used by a large number of industrial customers [12]. After three generations of development, these accelerators can now produce a wide spectrum of x-ray energies which are utilized to probe materials on a microscopic scale to determine their structure. These x-ray beams are more intense than can be obtained in any other way. They can be absorbed, reflected, scattered or refracted as they pass through the materials. These processes can be used in conjunction with the ability to "tune" the wavelength of the x-rays to identify specific elements and the structure of materials, including biological molecules.

Most industrial uses of synchrotron radiation accelerators are in the semiconductor, chemical and biomedical fields. Semiconductor applications include lithography, studies of material interfaces and other production issues. Applications in the chemical industry include the study of properties such as stress or texture of various materials produced, as well as the chemical reactions themselves. Applications in the biomedical field include protein crystallography, imaging molecular structures and studying molecular dynamics in tissue cells.

## 5. Industrial Accelerator Business

The market for industrial accelerators is surprisingly large and is growing at an increasing rate in many fields. Table II lists the numbers of accelerator systems sold to date for each broad industrial application, the current annual sales numbers and the range of current prices for the systems as estimated by the author in 2008 from published literature and vendor input.

TABLE II. TOTAL INDUSTRIAL ACCELERATOR SALES WORLDWIDE.

| Application | Total (2007) | Systems sold/yr | Sales/yr ($M) | System price ($M) |
|---|---|---|---|---|
| Ion Implantation | ~9500 | 500 | 1,400 | 1.5 – 5.0 |
| Electron beam modifications | ~4500 | 100 | 150 | 0.5 – 2.5 |
| Electron beam & X-ray irradiators | ~2000 | 75 | 130 | 0.2 – 8.0 |
| Ion beam analysis (including AMS) | ~200 | 25 | 30 | 0.4 – 1.5 |
| Radioisotope production (including PET) | ~550 | 50 | 70 | 1.0 – 30 |
| High energy x-ray inspection | ~650 | 100 | 70 | 0.3 – 2.0 |
| Neutron generators (including sealed tubes) | ~1000 | 50 | 30 | 0.1 – 3.0 |
| Total | 18,400 | 900 | 1780 | |

These data include a number of accelerators initially used for physics research, but now used mainly for industrial applications. The accelerator numbers reported here are larger than the previously published data on the installed base since many older accelerators are no longer in use, having been replaced by newer systems. It is clear that the industrial accelerator market has grown to be a significant international business. The present market for all industrial accelerators is estimated to be growing at a rate of almost 10% per year.

For the most part, the accelerators covered in this review are all available from commercial companies, from government backed companies, or government laboratories. All of the vendors known to the author are listed in Table III. This list changes often. New vendors appear as new systems are developed and others disappear as they are purchased by competitors or by other businesses in their application area. As an application matures, the size of each vendor usually increases but their numbers decrease due to the competitive nature of the business. The result is that the majority of accelerators sold each year are produced by just a few major vendors. However, there are usually a number of smaller vendors that pursue business in a particular geographic region or a niche market.

TABLE III: CURRENT INDUSTRIAL ACCELERATOR VENDORS.

| APPLICATION | EQUIPMENT VENDORS (LOCATION) |
|---|---|
| Ion Implantation | Varian Semiconductor Equipment (USA), Axcelis Technology (USA), Nissin Ion Equipment Co. (Japan), SEN Corp. (Japan), Applied Materials Inc. (USA), Ulvac Technologies (Japan), IHI Corp. (Japan), China Electronics Technology Group (China), Ibis Technology (USA), Advanced Ion Beam Technology (USA), High Voltage Engineering Europa (Netherlands), National Electrostatic Corporation (USA), Danfysik (Denmark) and Applied Energetics (USA). |
| Electron Beam Modification | Sciaky, Inc. (USA), All Welding Group AG (Germany), Cambridge Vacuum Engineering (England), Bodycote Techmeta (France), Pro-beam (Germany), Orion (Russia), Mirero (Korea), Omegatron (Japan), NEC Corporation (Japan), and Mitsubishi Electric Corporation (Japan). |

| APPLICATION | EQUIPMENT VENDORS (LOCATION) |
|---|---|
| Electron Beam Irradiation | Low energy systems: Energy Sciences, Inc. (USA), PCT Product & Manufacturing, LLC (USA), Ion Beam Applications SA (Belgium), Electron Crosslinking AB (Sweden), Advanced Electron Beams (USA), Wasik Associates (USA), and Nissin High Voltage Corp. (Japan).<br>High energy systems: Ion Beam Applications SA (Belgium), Nissin High Voltage Corporation (Japan), Denki Kogyo Co, Ltd. (Japan), IHI Corporation (Japan), L-3 Communications Pulsed Sciences Division (USA), Vivirad (France), Mevex (Canada) and the Budker Institute of Nuclear Physics (Russia), EB TECH Co., Ltd. (Korea), and the Center for Advanced Technology ( India). |
| Ion Beam Analysis | National Electrostatics Corporation (USA) and High Voltage Engineering Europa (Netherlands). |
| Radioisotope Production | GE Healthcare (Sweden), Siemens Medical Systems (USA), Ion Beam Applications SA (Belgium), Advanced Cyclotron Systems (Canada), Sumitomo Heavy Industries (Japan), Samyoung Unitech Co. (Korea), Thales GERAC (France) and AccSys Technology, Inc. (USA). |
| High Energy X-Ray Inspection | Varian Medical Security & Inspection Products (USA), and Nuctech (China). Other smaller vendors include L&W Research, Inc. (USA), HESCO (USA), EuroMeV (France), MEVEX (Canada) and JME Ltd. (UK). |
| Neutron Generators | D-T tubes: Thermo Scientific (USA), EADS Sodern (France) and All-Russia Research Institute of Automatics-VNIIA (Russia)<br>D-T tubes (internal use ): Halliburton Co.(USA), Schlumberger Well Services (France) and Baker Atlas (USA)<br>Accelerators: AccSys Technology, Inc. (USA), Ion Beam Applications SA (Belgium), Sumitomo Heavy Industries (Japan), National Electrostatics Corporation (USA) and High Voltage Engineering Europa (Netherlands). |
| Synchrotron Radiation | Oxford Instruments Accelerator Technology Group (UK), Danfysik (Denmark) and Sumitomo Heavy Industries (Japan). |

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