Accelerators in Industry

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Introduction

“Industrial accelerators” includes all accelerators producing charged particle beams except those for medical therapy and physics research.

- Category does not include devices generating internal beams (cathode ray tubes, x-ray tubes, rf tubes and electron microscopes or lithography systems).
- Category covers ~ 1/2 of all accelerators now being sold.
  (99% of all accelerators are non-research applications)

Presentation caveats:
- Vendors list changing constantly & valid through 2008.
- Sales estimates made by authors from publications and vendor input.

Presentation aim - Show that accelerators have a major socio-economic impact on society:
- All digital electronics (computers, cell phones, cameras, televisions, iPods, etc.)
- Many consumer products (tires, transmissions, food packaging, medical supplies)
- Health and environment (food, medical diagnostics, pollution control)

Many of these applications grew from world-wide accelerator technology developments, including nuclear and high-energy physics.

“Industrial Accelerators & Their Applications”

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Industrial Accelerator Technology

- **Direct Voltage** – Directly applied high voltage gradient used to accelerate charged particles (electrons or ions) – 10 kV to 10 MV.
  - Dynamitron & Cockcroft Walton generator – Basically voltage multiplier circuits at energies to up to 5 MeV and currents up to 100 mA.
  - Van de Graaff – Use a charge carrying belt or "chain". Energies from 1 to 15 MeV at currents from a few nA to a few mA.
  - Inductive Core Transformer (ICT) – A transformer charging circuit with energies to 3 MeV at currents to 50 mA.

- **RF Linacs** – Use RF generated voltage to accelerate "bunches" of charged particles
  - Electron linacs – Standing wave cavities from 0.8 to 9 GHz. Energies from 1 to 16 MeV at beam power to 50 kW.
  - Ion linacs – All use RFQs at 100 to 600 MHz. Energies from 1 to 70 MeV at beam currents up to mA.

- **Circular** – Magnetic field used to maintain circular orbit with rf acceleration.
  - Cyclotrons – Ion energies from 10 to 70 MeV at beam currents to several mA.
  - Betatrons – Electron energies to 15 MeV at few kW beam power.
  - Rhodotron – Electron energies from 5 to 10 MeV at beam power up to 700 kW.
  - Synchrotron – Electron energies up to 3 GeV and ion energies up to 300 MeV/amu.

Energy, current and beam power span more than six orders of magnitude.
Ion Implantation Accelerators

Accelerator Classifications

• Low Energy/ High Current
  • “High current implanters”
  • Ion energies from few hundred eV to tens of keV
  • Variable energy, single gap with currents to 50 mA

• Medium Energy/ Medium Current
  • Original ion implanter
  • Variable energies of 50 to 300 keV range
  • Currents in the 0.01 to 2 mA range
  • Usually multi-gap direct voltage units using voltage-multiplier HV power supply

• High Energy/ Low Current
  • Variable energy from 1 to 10 MeV
  • Beam currents to hundreds of microamperes
  • Can be linacs or tandem charge-exchange columns
  • Both use high-charge-states for upper energy range

These systems have become highly specialized and very reliable.

Equipment Suppliers

Major Vendors
Varian Semiconductor Equipment (USA)
Axcelis Technology (USA) & SEN Corp, (a joint venture in Japan with Sumitomo)
Nissin Ion Equipment Company (Japan)
Applied Materials – left the business in 2007

Miscellaneous Vendors
Ulvac Technologies & IHI Corp (Japan)
China Electronics Technology Group (China)
Ibis Technology (USA)
Advanced Ion Beam Technology (USA)
HVEE B.V. (Netherlands)
National Electrostatic Corporation (USA)
Danfysik (Denmark)

Annual sales of US$1.5B, with dopant materials US$140M.
Ion Implantation Applications

Semiconductors
- CMOS transistor fab for essentially all IC devices.
- CCD & CMOS imagers for cell phones & digital cameras
- Cleaving silicon for producing photovoltaic solar cells

Metals
- Harden cutting tools
- Reducing friction in metal parts
- Biomaterials for implants

Ceramics & glasses
- Harden surfaces
- Modify optics

All digital electronics now dependent on ion implantation. Typical IC has 25-30 implants during fabrication.
Electron Beam Material Processing

- **Typically a diode or triode electron gun**
  - Beam energy from 30 to 200 keV
  - Beam power from 6 to 200 kW
  - Beam used in vacuum or air

- **Major Vendors**
  - Sciaky, Inc. (USA)
  - All Welding Group AG (PTR Group and Steigerwald Strahltechnik) (Germany)
  - Cambridge Vacuum Engineering (UK)
  - Bodycote Techmeta (France)

- **Smaller Vendors**
  - Pro-beam (Germany)
  - Orion (Russia)
  - Mirero (Korea)
  - Omegatron (Japan)
  - NEC Corporation (Japan)
  - Mitsubishi Electric Corporation (Japan)

4000 systems in operation worldwide, with 1000 in US.

A mature business with large growth now in developing countries.
Electron Beam Materials Processing

- Application of electron guns dates to 1905
  - Critical to automotive production
    - Welding & hardening of parts
  - Dissimilar metals – deep welds
    - Speed gears
  - Precision cutting and drilling
    - 3000 holes/sec at 0.55 mm diameter
  - Recovery of refractory metals

Many factory systems fully automated.
Electron Beam Irradiation Accelerators

- 100 to 300 keV — Single gap, self-shielded sheet beam systems without beam scanning. Beam currents from 10 to 2000 mA; treat 1 to 3 m wide material. Used for curing thin film coatings and cross-linking laminates and single strand wire.

- 450 to 1000 keV — Larger dc systems with scanned beams and self-shielding. Beam currents from 25 to 250 mA; treat 0.5 to 2 meter wide material. Mainly used for cross-linking, curing and polymerization processes in the tire, rubber and plastics industry.

- 1 to 5 MeV — Scanned beam dc systems capable of 25 to 200 kW beam power; scanned beam width up to ~2 meters. Used for cross-linking and polymerization of thicker materials, and for sterilization of medical products.

- 5 to 10 MeV — High energy scanned beam systems capable of 25 to 700 kW beam power. Used for medical product sterilization and cross-linking and polymerization of even thicker materials. They are also used as x-ray generators for food irradiation, waste water remediation, and gemstone color enhancement for topaz and diamonds.

Covers a wide range of accelerator technology.
Electron Beam Irradiation Accelerator Vendors

**Low energy sheet beams**
- Energy Sciences, Inc. (USA)
- IBA (Belgium)
- Electron Crosslinking AB (Sweden)
- Advanced Electron Beams (USA)
- Wasik Associates (USA)
- Nissin High Voltage Corp. (Japan)
- PCT Prod. & Mfg, LLC, formerly RPC Industries (USA)

**High energy systems**
- IBA (Belgium), which owns RDI in the USA
- Nissin High Voltage Corporation (Japan)
- Denki Kogyo Co, Ltd. (Japan)
- IHI Corporation (Japan)
- Vivirad (France)
- Mevex (Canada)
- L-3 Communications Pulsed Sciences Division (USA)
- Budker Institute of Nuclear Physics (BINP) – Russia
  - EB TECH Co., Ltd. (Korea) – BINP collaboration
  - Center for Advanced Technology (India) – BINP collaboration

Now more than 1500 dedicated facilities worldwide.
Electron Beam Irradiator Applications

- Cross linking of materials (largest application)
- Sterilization of single-use disposable medical products – surgical gowns, surgical gloves, syringes, and sutures (growing applications)
- Food and waste irradiation (largest potential applications)

**Cross linking applications**

<table>
<thead>
<tr>
<th>Product</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross-linked polyethylene(PE) and PVC</td>
<td>Heat and chemical-resistant wire insulation; pipes for heating systems</td>
</tr>
<tr>
<td>Cross-linked polyurethane</td>
<td>Insulation, packing and flotation material</td>
</tr>
<tr>
<td>Cross-linked rubber sheet</td>
<td>High quality automobile tires</td>
</tr>
<tr>
<td>Cross-linked nylon</td>
<td>Cable insulation</td>
</tr>
<tr>
<td>Heat resistant SiC fibers</td>
<td>Heat and chemical resistant auto parts</td>
</tr>
<tr>
<td>Vulcanized rubber latex</td>
<td>Metal and ceramic composites</td>
</tr>
<tr>
<td>Cross-linked hydrogel</td>
<td>Surgical gloves and finger cots</td>
</tr>
<tr>
<td>Acrylic acid grafted PE film</td>
<td>Wound dressings</td>
</tr>
<tr>
<td>Grafted polyethylene fiber</td>
<td>Battery separators</td>
</tr>
<tr>
<td>Curing of paints and inks</td>
<td>Deodorants</td>
</tr>
<tr>
<td>Curing of paints and inks</td>
<td>Surface coating and printing</td>
</tr>
</tbody>
</table>

Total of $50 billion per year

This application involves many consumer products.
Radioisotope Production

- **Applications** (>50 routine radioisotopes)
  - Industrial – Gauging & calibration
  - Medical – Diagnostics & treatment
    - SPECT
    - PET
    - Brachytherapy

- **Cyclotrons & Linacs** – both protons & deuterons
  - PET – self shielded systems from 7 to 18 MeV with current < 200 µA)
  - SPECT – energies from 22 to 70 MeV with currents up to 2 mA

- **Vendors**
  - 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)
  - AccSys Technology, Inc. (USA)

Large growth in compact accelerators for PET.
Ion Beam Analysis

- **Techniques** – All were adapted from nuclear physics measurements
  - Rutherford Back Scattering (RBS)
  - Elastic Recoil Detection Analysis (ERDA)
  - Nuclear Reaction Analysis (NRA)
  - Particle Induced X-ray Emission (PIXE)
  - Particle Induced Gamma ray Emission (PIGE)
  - Nuclear Resonance Reaction Analysis (NRRA)
  - Resonant Scattering Analysis (RSA)
  - Charged Particle Activation Analysis (CPAA)
  - **Accelerator Mass Spectrometry (AMS)**

- **Accelerators**
  - Electrostatic – 100’s of keV to several MeV

- **Vendors**
  - National Electrostatic Corp. (USA)
  - High Voltage Engineering Europa (Netherlands)

**Applications**
- Semiconductor quality
- Environmental monitoring
- Geological studies
- Oceanography studies
- Biomedical science
- Renewable energy

These applications still widely used at many research labs.
High Energy X-Ray Inspection

- **Accelerators**
  - Medical system “spin-offs”
  - Electron linacs & betatrons – 1 to 16 MeV

- **Applications**
  - Radiography of large castings
  - Examination of rocket motors and munitions
  - Port examination of containers & semi-trailers

- **Major Vendors**
  - Varian Medical Security & Inspection Products (USA)
  - Nuctech (China)

- **Smaller Vendors**
  - L & W Research (USA)
  - HESCO (USA)
  - EuroMeV (France)
  - MEVEX (Canada)
  - JME Ltd. (UK)

Now more than 1000 systems, growing at 15% per year worldwide.
Neutron Production Accelerators

Technology

• “Open” vacuum systems – Larger accelerators (MeV) using many different targets.

• Sealed “tubes” – Small electrostatic units employing (d,t) and (d,d) reactions.

Vendors

• Principal vendors for sealed tubes:
  • Thermo Scientific (USA)
  • Adelphi Technology, Inc (USA)
  • EADS Sodern (France) and
  • All-Russia Research Institute of
    Electronics VNIIA (Russia)

• Large US producers for oil well logging:
  • Halliburton Co,
  • Schlumberger Well Services
  • Baker Atlas

• Accelerator-based generator vendors:
  • AccSys Technology, Inc. — p and d linacs
  • IBA — Dynamitron
  • Sumitomo Heavy Industries — cyclotrons
  • NEC and HVEE — electrostatic accelerators
Neutron Generator Applications

- Security applications (contraband detection and nuclear and chemical analysis).

- Trace element analysis, including biological and environmental measurements.

- Bulk material analysis, including oil well logging and gold, cement and scrap metal on-line monitoring.

- Now replacing many radioactive neutron sources due to new US regulations on control of these sources.

- More than 200 units produced per year.

- Industrial use is dwarfed by military use in nuclear weapons.

Oil well logging is largest application of these systems.
Synchrotron Radiation

Properties of Synchrotron Radiation

- Continuous spectrum (1 eV – 100 keV, most intense spectrum in the VUV and X-ray region).
- Collimation (1 mrad).
- Linear polarization (> 95% in the plane of the electron orbit).
- Circular polarization (up to 90% above and below the plane of the electron orbit).
- Partly coherent.
- Completely calculable.
- “Clean” source, i.e. emission of radiation takes place under ultra-high vacuum conditions.
- Time structure allows time resolved experiments (determined by length of the “electron bunches” in the accelerator).

Vendors:
- Oxford Instruments Accelerator Technology Group (UK) – several superconducting systems for semiconductor lithography.
- Danfysik (Denmark) – normal conducting systems in Canada and Australia.
- Sumitomo Heavy Industries (Japan) – compact normal conducting systems.
Synchrotron Radiation Applications

**Techniques:**
- Fourier Transform Infra-red spectroscopy
- Infrared Micro-spectroscopy
- Circular dichroism
- UV-VUV Photo-electron spectroscopy (ESCA)
- VUV-microspectroscopy
- Powder diffraction
- Surface diffraction
- Small angle X-ray scattering + wide angle X-ray scattering (SAXS-WAXS)
- Protein Crystallography
- Microtomography
- X-ray fluorescence (XRF) and X-ray microscopy
- X-ray Absorption Spectroscopy: EXAFS, XANES

**Fabrication techniques:**
- UV-VUV lithography (Microelectronics)
- X-ray lithography (LiGA) for MEMS (Sensors, gears, etc.)

**Fields:**
- Semiconductor industry – includes lithography, studies of material interfaces and other production issues.
- Chemical industry – studies of properties such as stress or texture of various materials produced and the chemical reactions themselves.
- Biomedical field – includes protein crystallography, imaging molecular structures and molecular dynamics studies in tissue cells.

Most industrial applications being conducted on more than 60 research systems worldwide.
### Industrial Accelerator Business*

<table>
<thead>
<tr>
<th>Industrial Application</th>
<th>Systems thru 2008</th>
<th>Systems sold/yr</th>
<th>Sales/yr ($M)</th>
<th>System price ($M)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ion Implantation</td>
<td>~10,000</td>
<td>500</td>
<td>1,500</td>
<td>1.5 – 5.0</td>
</tr>
<tr>
<td>Electron beam modifications</td>
<td>~7,000</td>
<td>100</td>
<td>150</td>
<td>0.5 – 2.5</td>
</tr>
<tr>
<td>Electron beam &amp; X-ray irradiators</td>
<td>~2,000</td>
<td>75</td>
<td>130</td>
<td>0.2 – 8.0</td>
</tr>
<tr>
<td>Ion beam analysis (including AMS)</td>
<td>~200</td>
<td>25</td>
<td>30</td>
<td>0.4 – 1.5</td>
</tr>
<tr>
<td>Radioisotope production (including PET)</td>
<td>~600</td>
<td>50</td>
<td>70</td>
<td>1.0 – 30</td>
</tr>
<tr>
<td>High energy x-ray inspection</td>
<td>~750</td>
<td>100</td>
<td>70</td>
<td>0.3 – 2.0</td>
</tr>
<tr>
<td>Neutron generators (including sealed tubes)</td>
<td>~2,000</td>
<td>50</td>
<td>30</td>
<td>0.1 – 3.0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>22,550</strong></td>
<td><strong>900</strong></td>
<td><strong>1880</strong></td>
<td></td>
</tr>
</tbody>
</table>

*New preliminary numbers from book chapters.

**Total sales increasing almost 10% per year.**

All the products that are processed, treated or inspected by particle beams have an annual value exceeding US$500B.
Future Technology & Applications

- **Free Electron Laser (FEL)**
  - Next generation of synchrotron light source.
  - Uses electrons from linac with PM wiggler to create tunable light source for many applications now performed at electron synchrotron facilities.

- **Superconducting Linacs & Cyclotrons**
  - Improvements in cryogenic technology from widespread use in large research and medical accelerators.
  - Increase in efficiency and size reduction of systems for cancer therapy, and radioisotope and neutron production.

- **Fixed Field Alternating Gradient (FFAG) Cyclotron**
  - Being developed for high energy physics research at national labs.
  - Also being developed as a neutron source for BNCT and, if proven, will be quickly adapted for other neutron beam applications.

Other R&D underway, but is kept secret for competitive reasons.