Review of Industrial Accelerators and Their Applications

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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.

- Talk and paper “notices”:
  - Vendors list changing constantly & valid through 2007.
  - Sales estimates made by author from publications and vendor input.
  - Applications descriptions are brief and from experts in each application.

- Purpose - Show that accelerators have a huge socio-economic impact:
  - All electronics
  - Many consumer products

Presentation based on article written for Reviews of Accelerator Science & Technology and on research for book on “Industrial Accelerator & Their Applications”, edited by R. W. Hamm & M. E. Hamm to be published by World Scientific Publishing
Industrial Accelerators

- **Direct Voltage** – Voltage gradient used to accelerate charged particles (electrons or ions)
  - Van de Graaff – Use a charge carrying belt or “chain”. Energies range from 1 to 15 MeV at currents from a few nA to a few mA.
  - Dynamitron & Cockcroft Walton generator – Basically voltage multiplier circuits at energies to up to 5 MeV and currents up to 100 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 to maintain circular orbit.
  - 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.
Industrial Applications of Accelerators:

- Ion Implantation
- Electron beam materials processing
- Electron beam irradiators
- Radioisotope production
- Ion Beam Analysis
- High Energy X-ray Inspection
- Neutron generators
- Synchrotron radiation

Range from small dedicated accelerators to large shared facilities.
Ion Implantation

Semiconductors
- CMOS fabrication
- SIMOX
- Cleaving silicon
- MEMS

Metals
- Harden cutting tools
- Artificial human joints

Ceramics & glasses
- Harden surfaces
- Modify optics

All digital electronics now dependent on ion implantation.
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 reliable.
Ion Implantation Accelerator Sales

Estimated Implanter Units Sold
Based on Revenue Data
Med & High Current, High Energy
Incomplete Data from Japan before 1990
Total Units = 7,410

Year

Total Units Sold per Year


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

Misc. 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)
Electron Beam Materials Processing

- Application of electron guns dating to 1905
  - Critical to automotive production
  - Refractory metals
  - Dissimilar metals
  - Precision cutting and drilling
- Beam energy from 60 to 200 keV
- Beam power from 6 to 200 kW

- 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)

A mature business with large growth now in developing countries
Electron Beam Irradiators

- 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)</td>
<td>Heat and chemical-resistant wire insulation;</td>
</tr>
<tr>
<td>and PVC</td>
<td>pipes for heating systems</td>
</tr>
<tr>
<td>Cross-linked foam polyethylene</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 polyurethane</td>
<td>Cable insulation</td>
</tr>
<tr>
<td>Cross-linked nylon</td>
<td>Heat and chemical resistant auto parts</td>
</tr>
<tr>
<td>Heat resistant SiC fibers</td>
<td>Metal and ceramic composites</td>
</tr>
<tr>
<td>Vulcanized rubber latex</td>
<td>Surgical gloves and finger cots</td>
</tr>
<tr>
<td>Cross-linked hydrogel</td>
<td>Wound dressings</td>
</tr>
<tr>
<td>Acrylic acid grafted PE film</td>
<td>Battery separators</td>
</tr>
<tr>
<td>Grafted polyethylene fiber</td>
<td>Deodorants</td>
</tr>
<tr>
<td>Curing of paints and inks</td>
<td>Surface coating and printing</td>
</tr>
</tbody>
</table>

This field covered very thoroughly at this meeting (see SM/EB session).
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
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
- 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)**

Applications
- Semiconductor quality
- Environmental monitoring
- Geological studies
- Oceanography studies
- Biomedical science

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

These applications still widely used at many research labs (see SM/AE session).
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)

See paper SM/EB-28
Neutron Generators

Applications

• Cancer therapy, including BNCT
• NDE, including security checking
• Material analysis

Vendors

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

See SM/EN session
Synchrotron Radiation

■ Application 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.

■ 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

Most industrial applications being conducted on research systems, as described in papers in Session SM/SA.
**Industrial Accelerator Business**

<table>
<thead>
<tr>
<th>Application</th>
<th>Total (2007)</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>~9500</td>
<td>500</td>
<td>1,400</td>
<td>1.5 – 5.0</td>
</tr>
<tr>
<td>Electron beam modifications</td>
<td>~4500</td>
<td>100</td>
<td>150</td>
<td>0.5 – 2.5</td>
</tr>
<tr>
<td>Electron beam &amp; X-ray irradiators</td>
<td>~2000</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>~550</td>
<td>50</td>
<td>70</td>
<td>1.0 – 30</td>
</tr>
<tr>
<td>High energy x-ray inspection</td>
<td>~650</td>
<td>100</td>
<td>70</td>
<td>0.3 – 2.0</td>
</tr>
<tr>
<td>Neutron generators (including sealed tubes)</td>
<td>~1000</td>
<td>50</td>
<td>30</td>
<td>0.1 – 3.0</td>
</tr>
<tr>
<td>Total</td>
<td>18,400</td>
<td>900</td>
<td>1780</td>
<td></td>
</tr>
</tbody>
</table>

Total accelerators sales increasing almost 10% per year.
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