Accelerators in Industry

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High Energy Physics Advisory Panel
Bethesda, MD
March 12, 2010

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.**

Presentation based on preliminary input to the book "Industrial Accelerators & Their Applications", edited by R. W. Hamm & M. E. Hamm, to be published by World Scientific Publishing.

“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

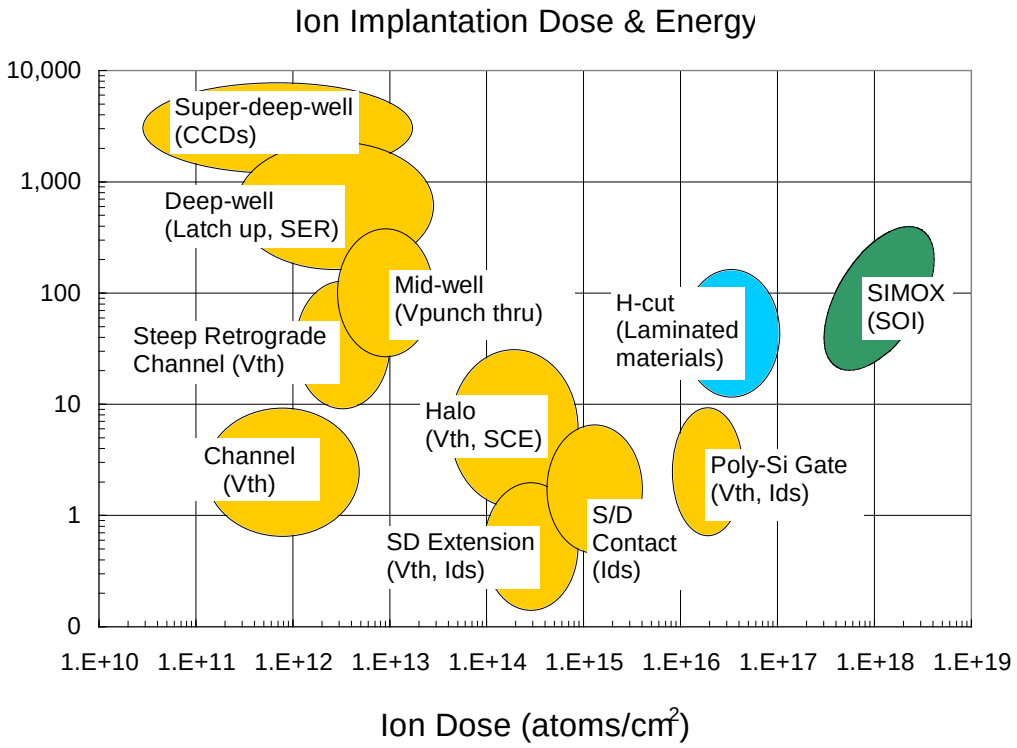
- CMOS transistor fab for essentially all IC devices.
- CCD & CMOS imagers for cell phones & digital cameras
- Cleaving silicon for producing photovoltaic solar cells

Metals

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

Ceramics & glasses

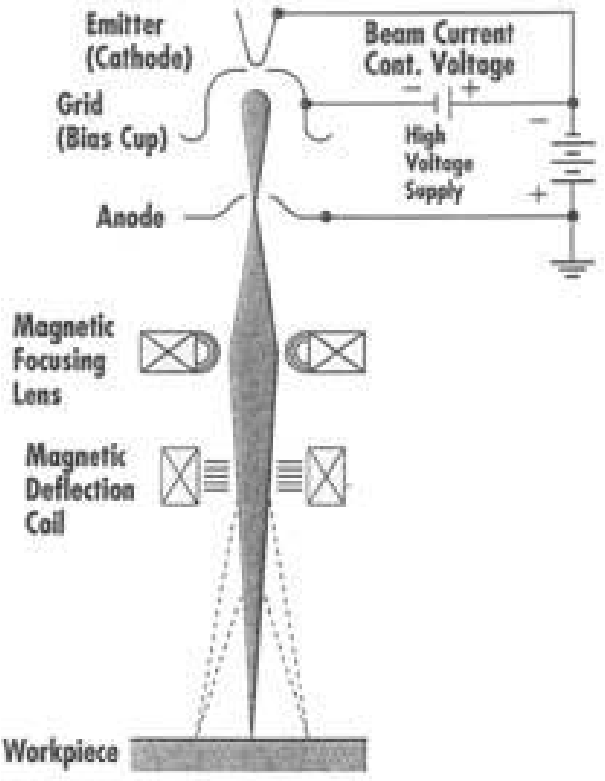
- Harden surfaces
- Modify optics



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)

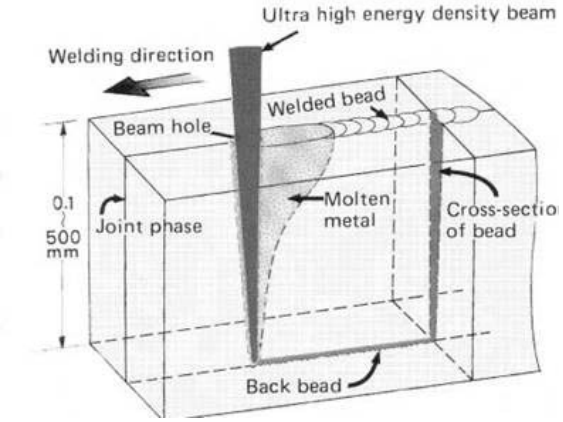


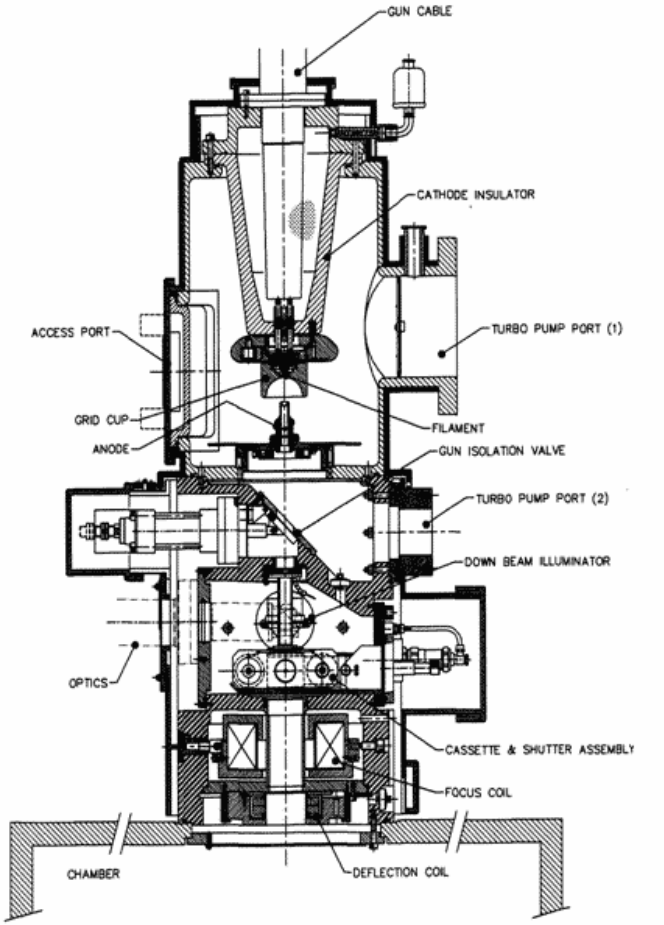
4000 systems in operation worldwide, with 1000 in US.

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.

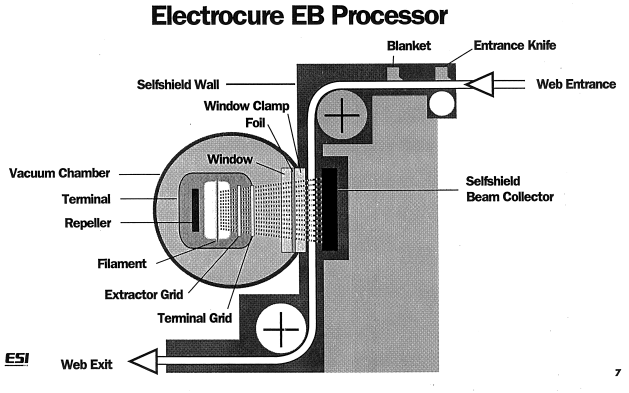
- 1 to 5 MeV — Scanned beam dc systems capable of 25 to 200 kW beam power; scanned beam width up to ~2 meters. Used for cross-linking and polymerization of thicker materials, and for sterilization of medical products.

- 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.

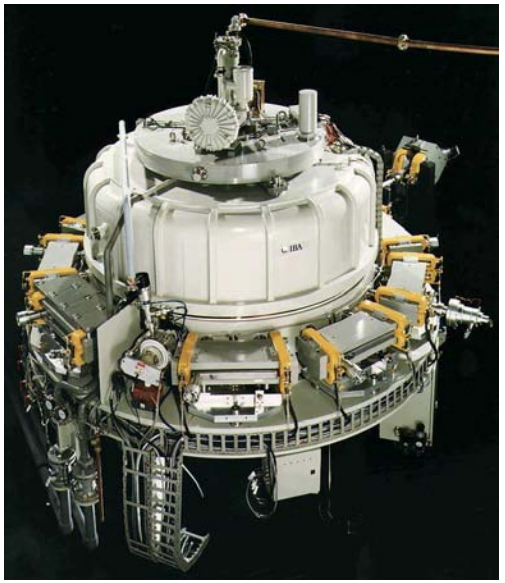
Covers a wide range of accelerator technology.

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.

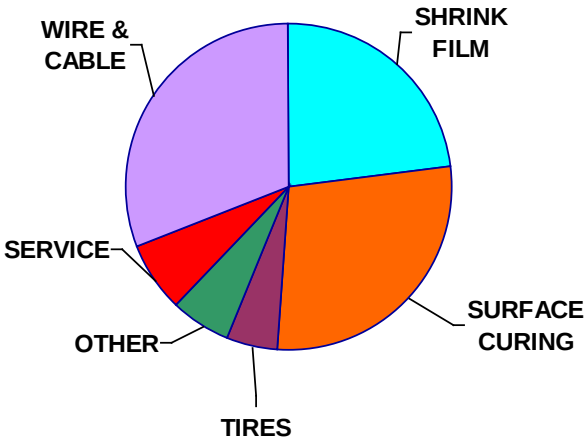
Electron Beam Irradiator Applications

- 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

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

Cross linking by industry



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

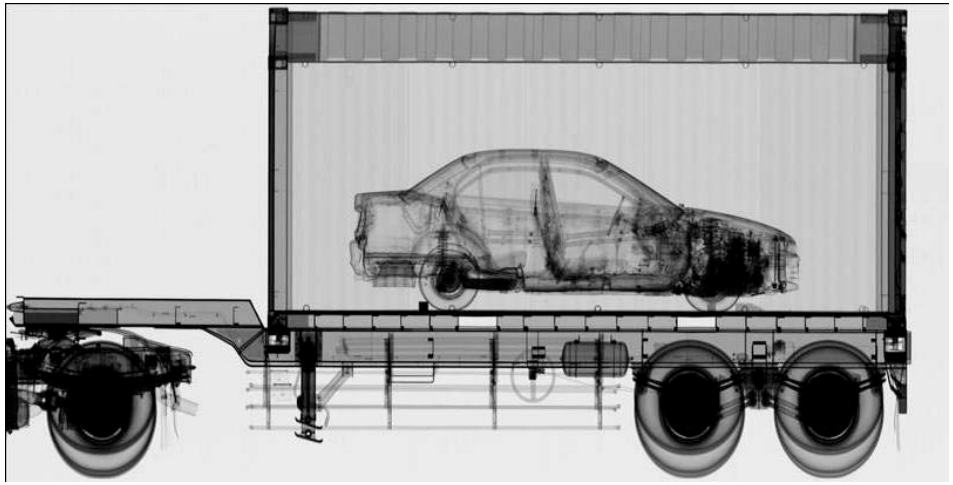
- Semiconductor quality
- Environmental monitoring
- Geological studies
- Oceanography studies
- Biomedical science
- Renewable energy

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.

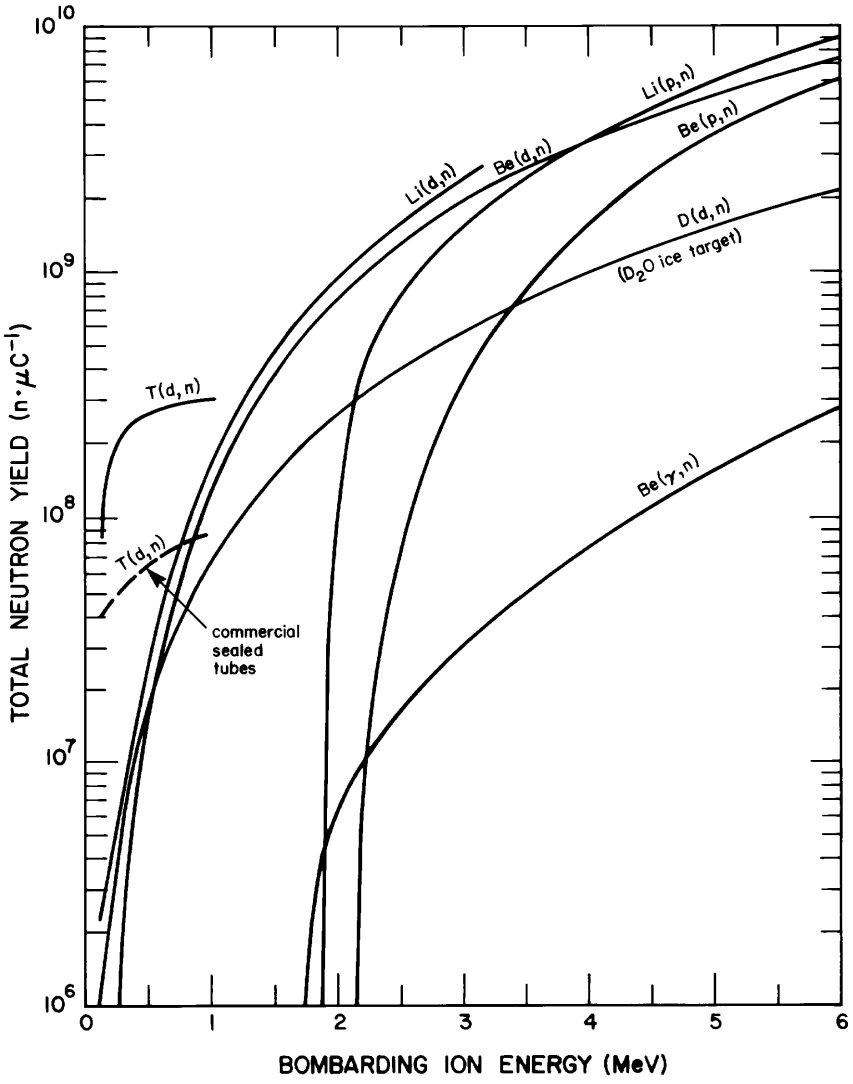
• Sealed “tubes” – Small electrostatic units employing (d,t) and (d,d) reactions.

Vendors

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



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.

Workers preparing a small-diameter well probe that contains a neutron generator for use in logging an existing oil well borehole.

Oil well logging is largest application of these systems.

Synchrotron Radiation

Properties of Synchrotron Radiation

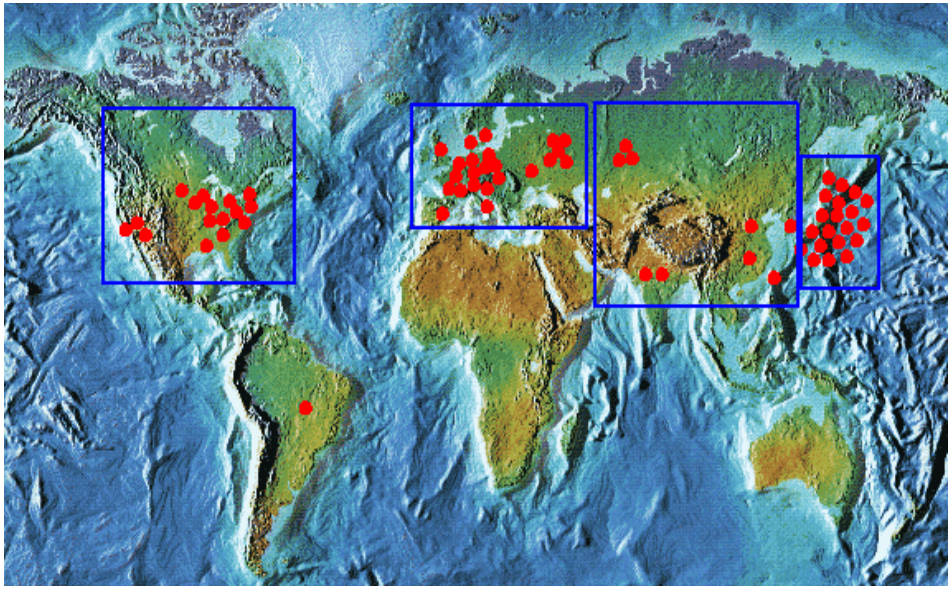
- Continuous spectrum (1 eV – 100 keV, most intense spectrum in the VUV and X-ray region.
- Collimation (1 mrad).
- Linear polarization (> 95% in the plane of the electron orbit).
- Circular polarization (up to 90% above and below the plane of the electron orbit).
- Partly coherent.
- Completely calculable.
- “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**
- **<u>Fabrication techniques:</u>**
  - **UV-VUV lithography (Microelectronics)**
  - **X-ray lithography (LiGA) for MEMS (Sensors, gears, etc.)**



Most industrial applications being conducted on more than 60 research systems worldwide.

- **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.

Industrial Accelerator Business*

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

*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.