



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

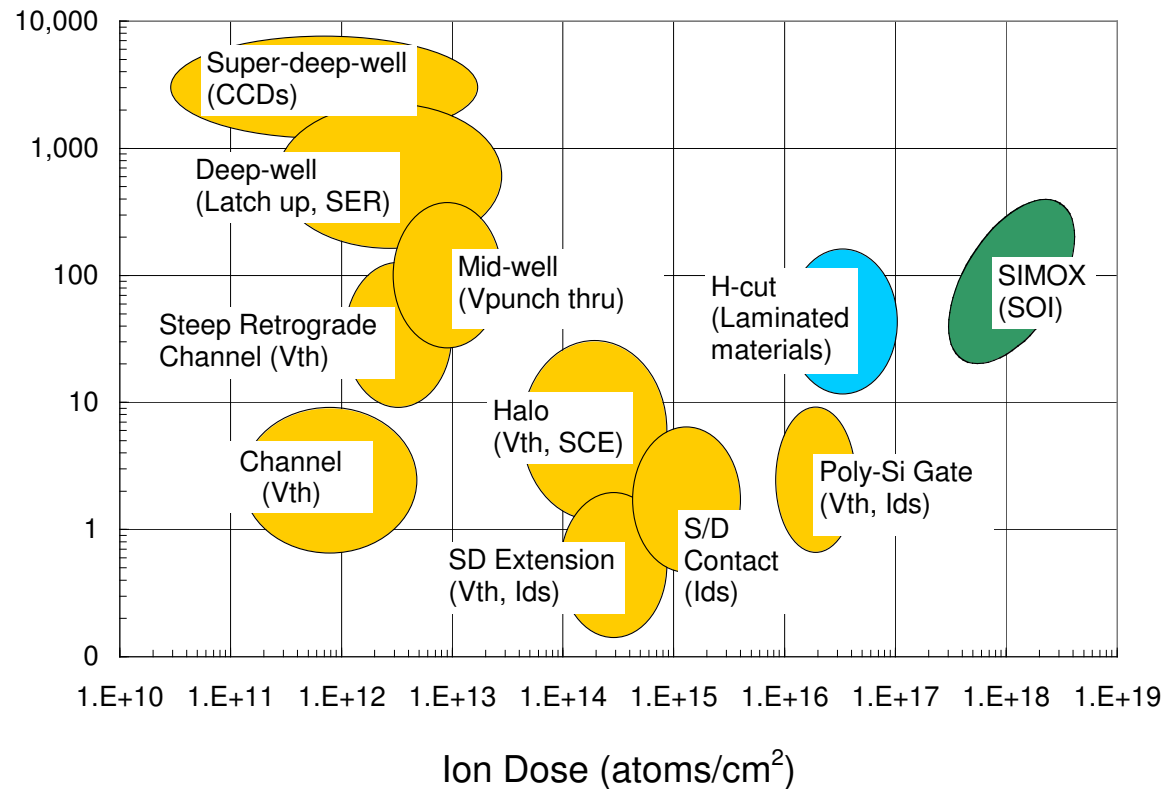
Metals

- Harden cutting tools
- Artificial human joints

Ceramics & glasses

- Harden surfaces
- Modify optics

Ion Implantation Dose & Energy



All digital electronics now dependent on ion implantation.

Ion Implantation Accelerators

Accelerator classifications

•Low energy/ high current

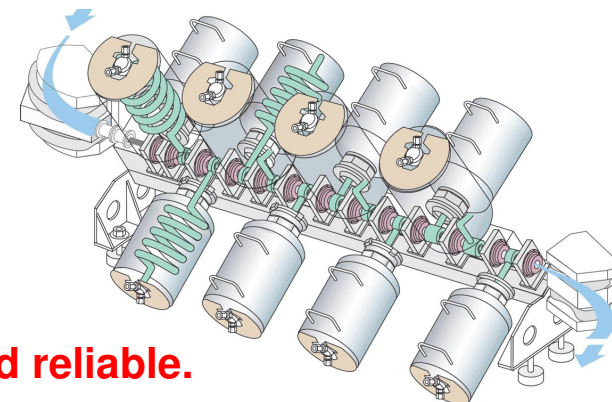
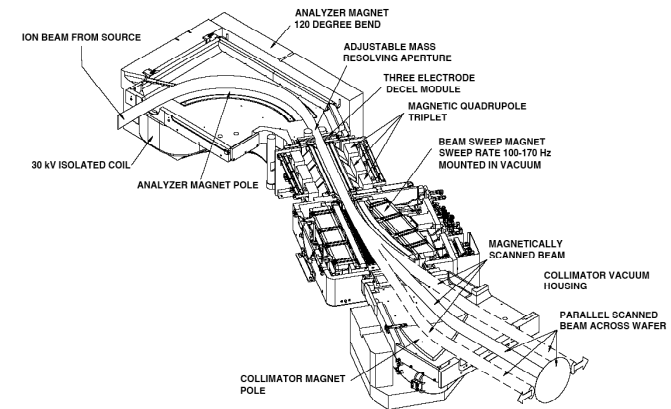
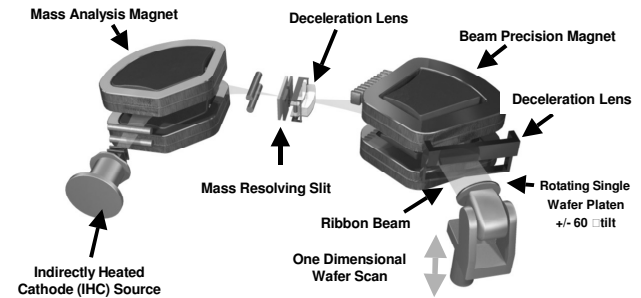
- “High current implanters”
- Ion energies from few hundred eV to tens of keV.
- Variable energy, single gap with currents to 50 mA.

•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.

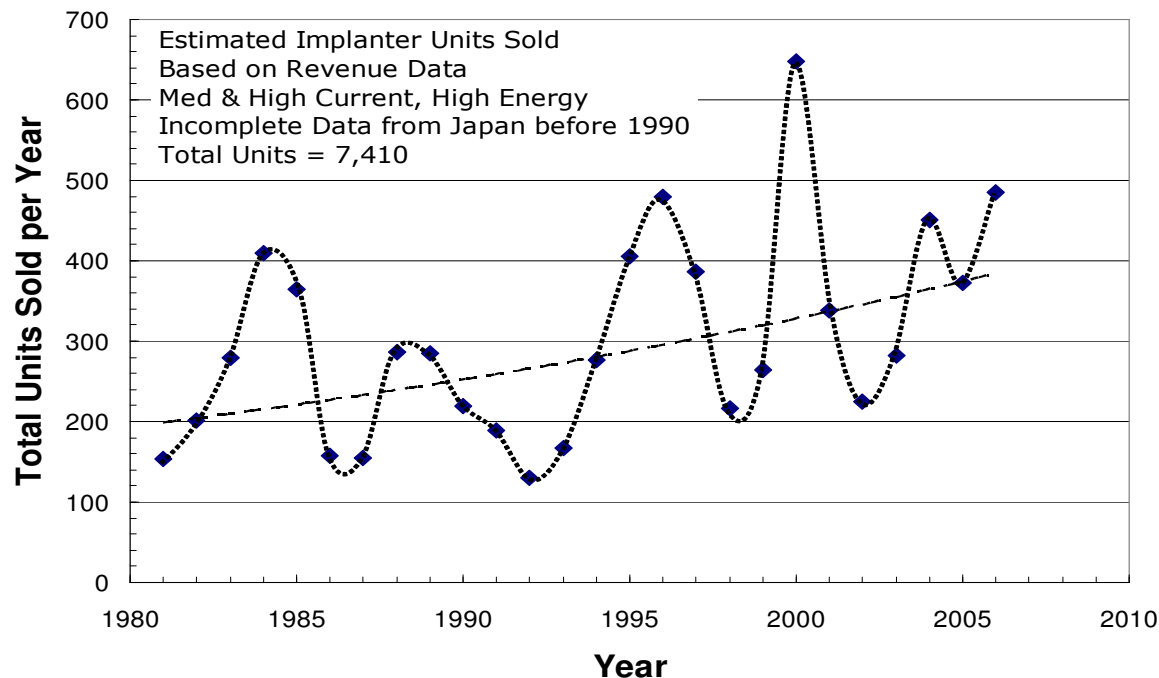
•High energy/ low current

- 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



Major Vendors

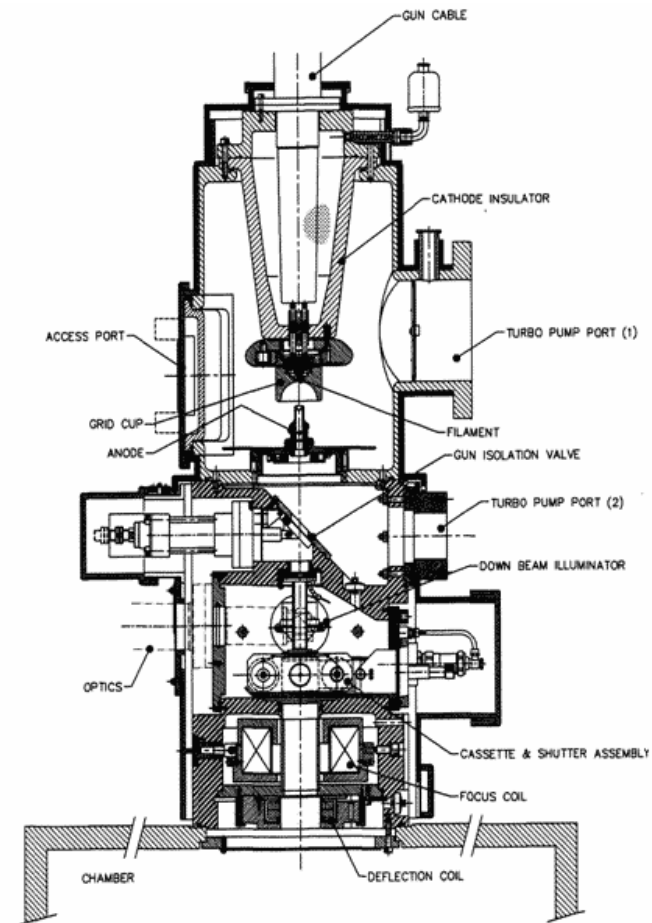
- Varian Semiconductor Equipment (USA)
- Axcelis Technology (USA) & SEN Corp., a joint venture in Japan with Sumitomo
- Nissin Ion Equipment Company (Japan)
- Applied Materials – left the business in 2007

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

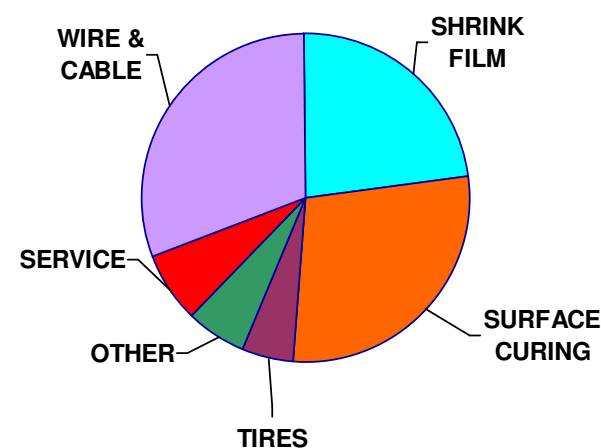
Electron Beam Irradiators

- 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

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 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.

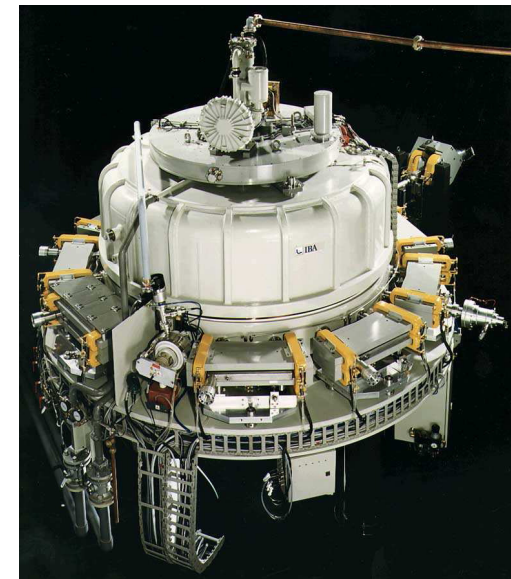
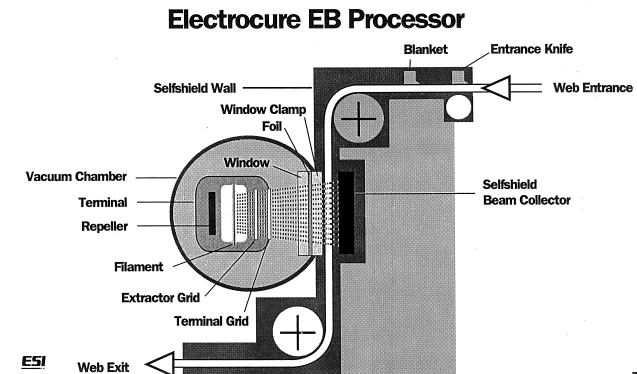
Electron Beam Irradiation Accelerator Vendors

■ 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

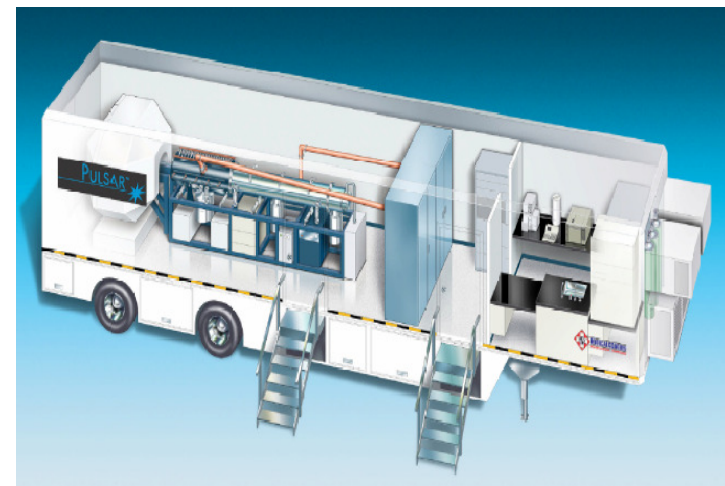
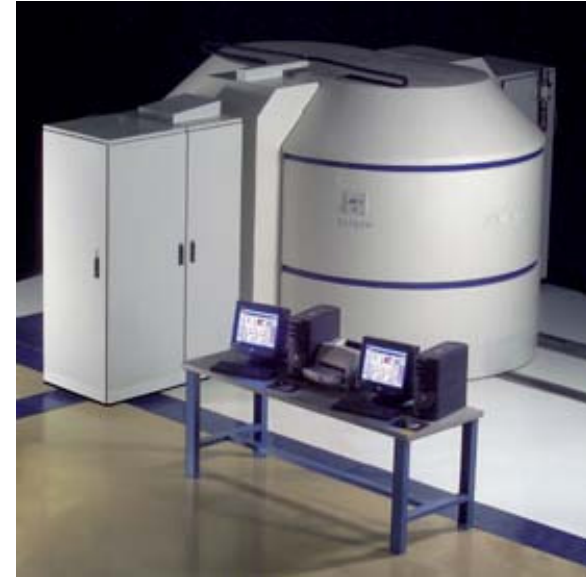


Radioisotope Production

- **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 μ A)
 - 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)**

■ Vendors

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

Applications

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



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

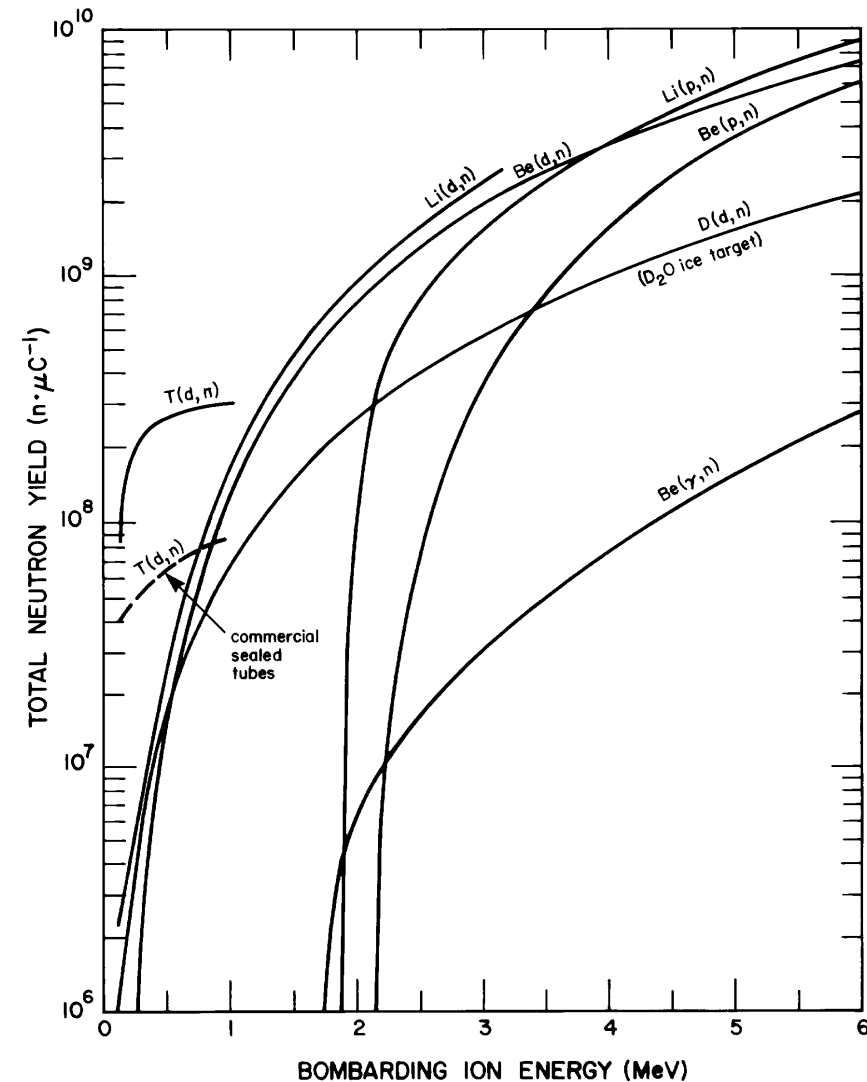
Neutron Generators

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

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	

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