Current & Future Industrial Applications of Accelerators

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October 4, 2013

NA-PAC-13
Pasadena, California

Presentation Outline

- Introduction to “Industrial Accelerators”
- The “Beam Business” Statistics
- Current Industrial Accelerator Applications
- Future Industrial Accelerator Applications
- Concluding Remarks

Introduction to Industrial Accelerators

- "***Industrial Accelerators***" – All accelerators producing charged particle beams for use in all applications but medical therapy and physics research.
  - Category does not include internal beam devices (cathode ray tubes, X-ray tubes, rf tubes, electron microscopes or lithography systems).
  - Specialized industrial accelerator applications also not included:
    - ✓ Focused ion beams (FIB) used in the semiconductor industry for the inspection and ablation of materials.
    - ✓ Ion beam figuring (IBF), a relatively new technique used in preparing optical and nano-material surfaces.
- Category covers >50% of all accelerators now being sold.

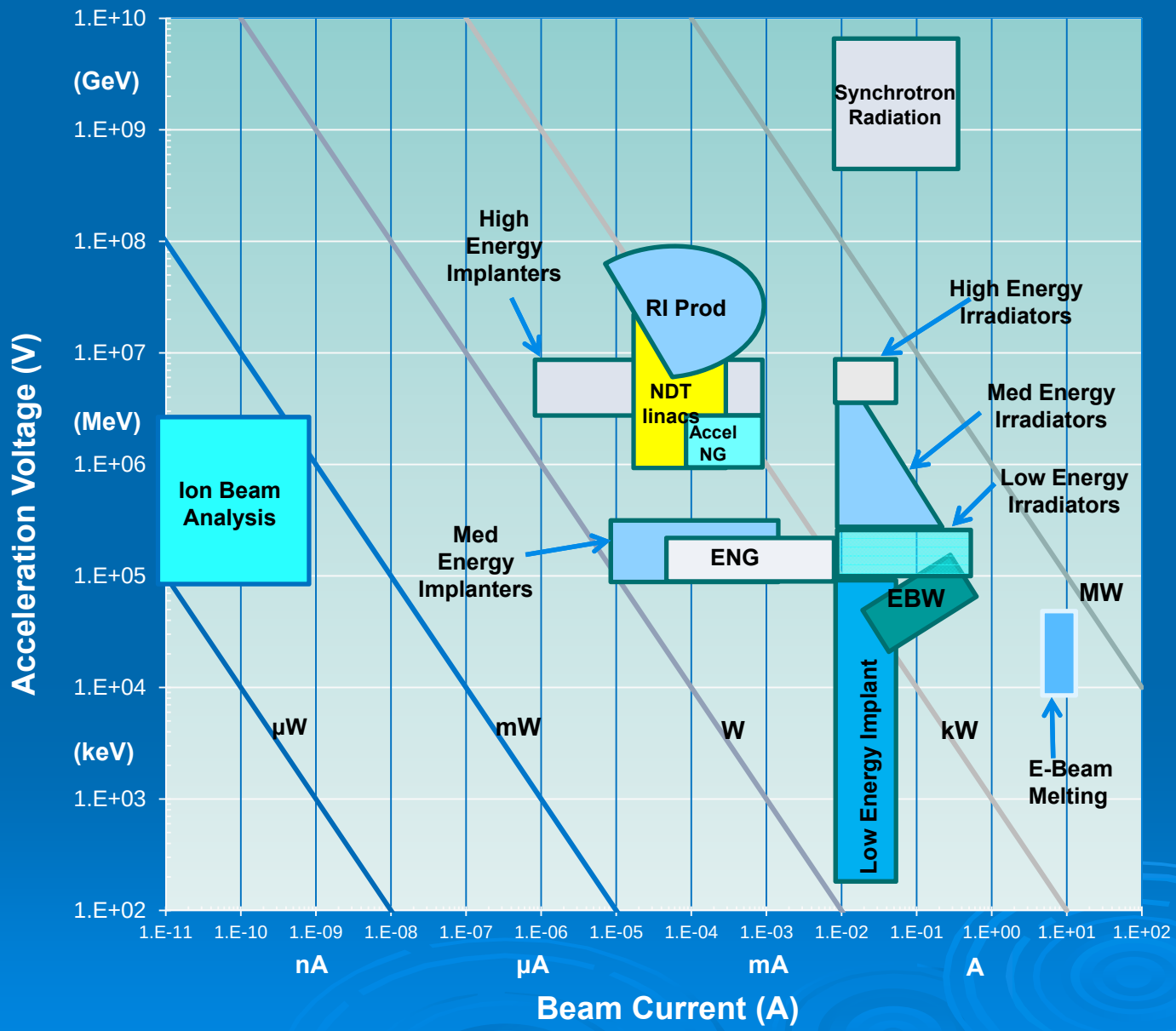
5 Invited & 5 contributed oral presentations at NA-PAC 13

Accelerators for Industrial Applications

- **Direct Voltage:** DC voltage to accelerate either electrons or ions.
  - **Dynamitron & Cockcroft Walton generator.** Energies to 5 MeV and currents up to 100 mA.
  - **Van de Graaff.** Energies from 1 to 15 MeV at currents of a few nA to a few mA.
  - **Inductive Core Transformer (ICT).** Energies to 3 MeV at currents up to 50 mA.
- **RF Linacs:** A wide range of operating rf frequencies for charged particles.
  - **Electron linacs.** Standing wave and traveling wave cavities from 0.8 to 9 GHz. Energies from 1 to 16 MeV at beam powers to 50 kW.
  - **Ion linacs.** All use RFQs at 100 to 600 MHz. Energies from 1 to 70 MeV at beam currents up to >1 mA.
- **Circular Accelerators:** As usually covered at this conference.
  - **Betatrons.** Electron energies to 15 MeV at few kW beam power.
  - **Cyclotrons.** Ion energies from 10 to 70 MeV at beam currents to several mA.
  - **Rhodotrons.** Electron energies from 5 to 10 MeV at beam powers up to 700 kW.
  - **Synchrotrons.** Electron energies to 3 GeV and ion energies to 300 MeV/amu.

Energy, current, and beam power span many orders of magnitude.

Industrial Accelerator Operating Regimes



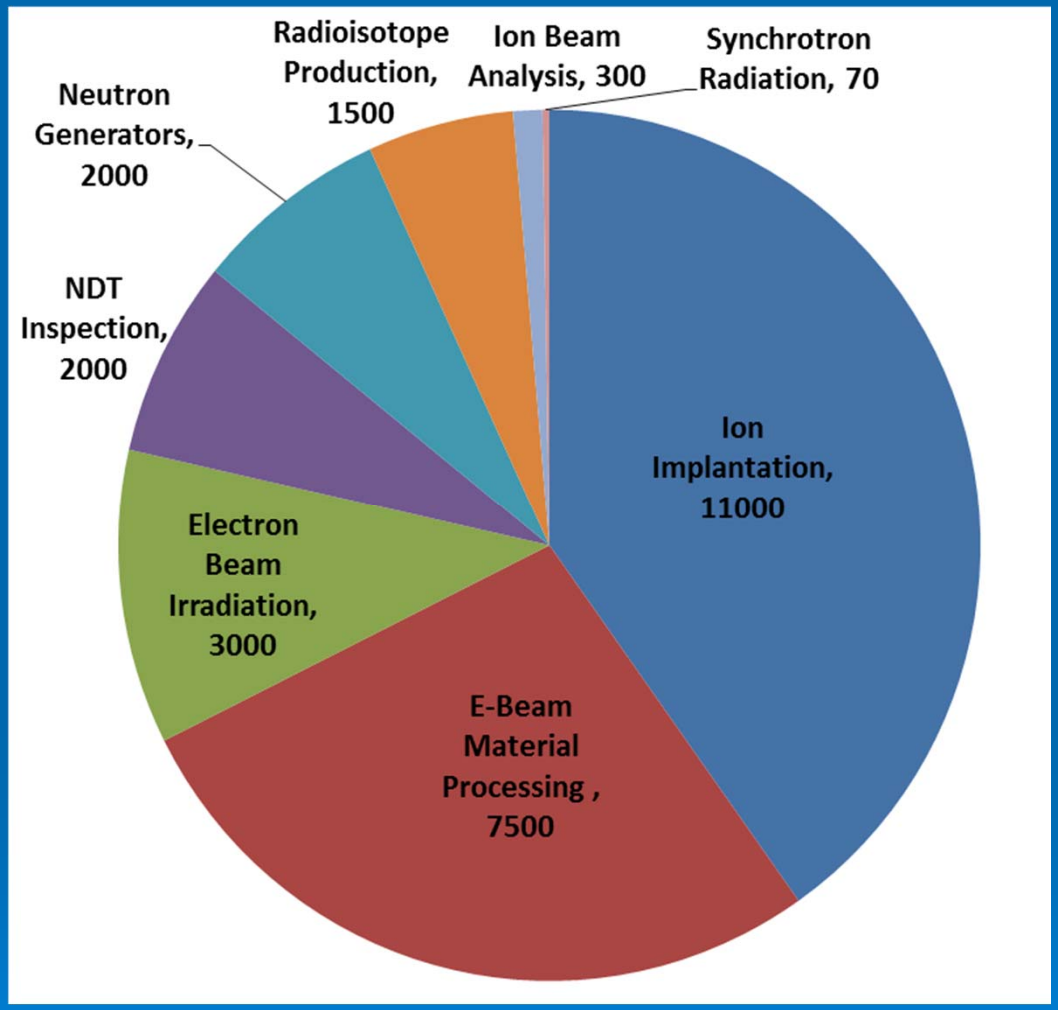
Industrial Accelerator Development

- Most modern industrial accelerator technology concepts were originally developed in the 1930s for physics research devices.
- Soon after a new type of accelerator was invented someone recognized its potential for practical applications.
- Industrial accelerators have evolved into high quality products often tailored to a specific application with new technology developed just for these applications.
- Full market acceptance takes decades.

Early Accelerator Technology Transfers

- Electron linacs – Varian collaboration with SLAC and later adoption of SCL from LANL for cancer therapy and later for industrial applications.
- Cyclotrons for radioisotope production – early company was The Cyclotron Corporation (LBNL), using technology directly from LBNL.
- Ion implantation – Manhattan Project isotope separators at ORNL and tandem technology used for original development of this tool.
- Sealed tube neutron generators – spin-off from DOD programs for nuclear detonators.

Commercial Accelerator Business



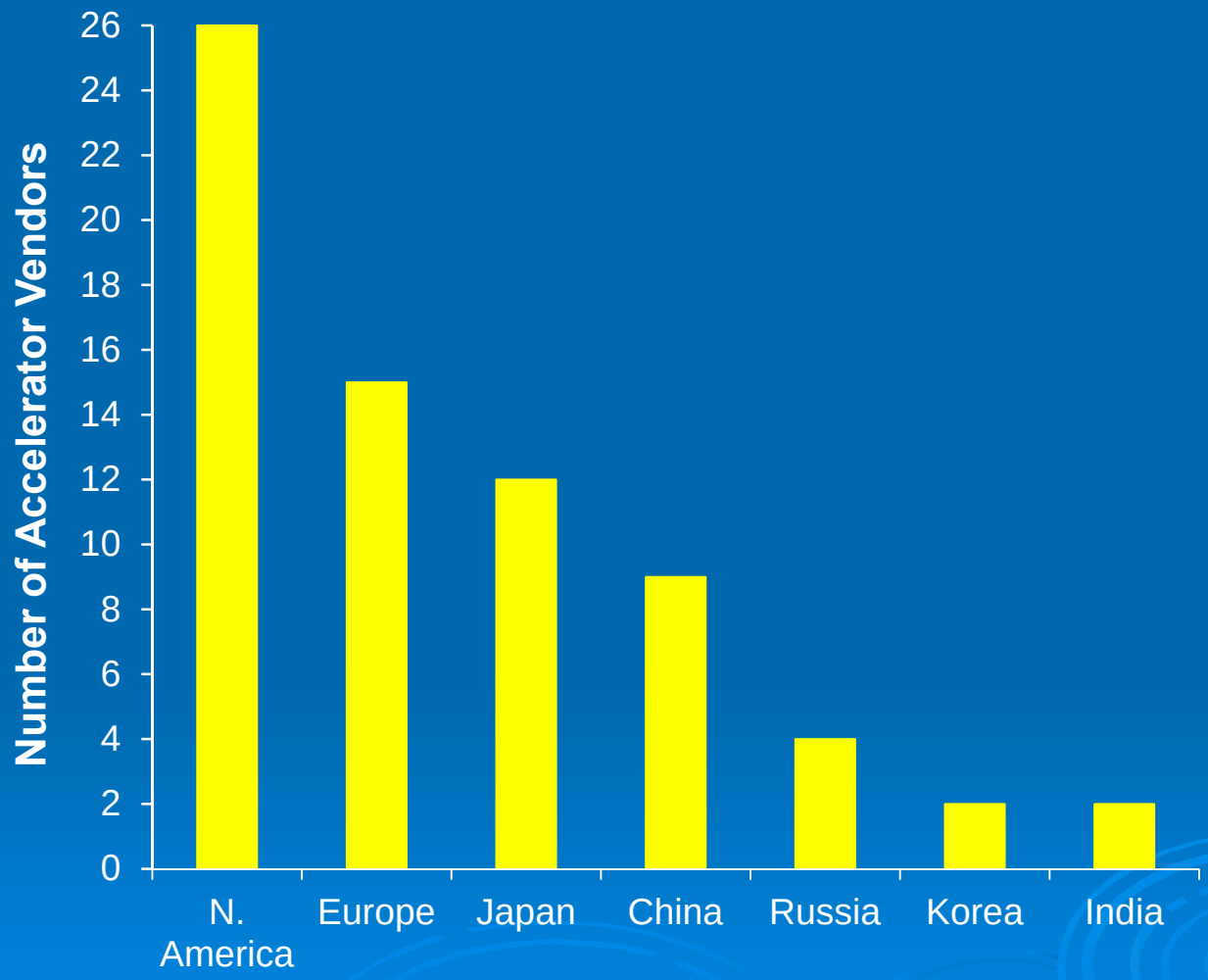
Updated totals indicate that >27,000 systems have been sold and estimates are >20,000 still in operation today.

More than 70 vendors worldwide are in the accelerator business.

Vendors are primarily in US, Europe and Japan, but growing in China, Russia and India

The products that are processed, treated or inspected by particle beams had an annual value >US$500B in 2010.

Accelerator Vendors Worldwide



Industrial Accelerator Applications

Well established commercial applications

- Ion Implantation for Semiconductors and Materials
- Electron Beam Material Processing
- Electron Beam Materials Irradiators
- Production of Radioisotopes

Rapidly growing commercial applications

- Ion Beam Analysis
- Analysis using Neutron Generators
- Non-destructive Testing & Inspection
- Synchrotron Radiation

Ion Implantation Applications

S. Felch – WEYB2

Semiconductors

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

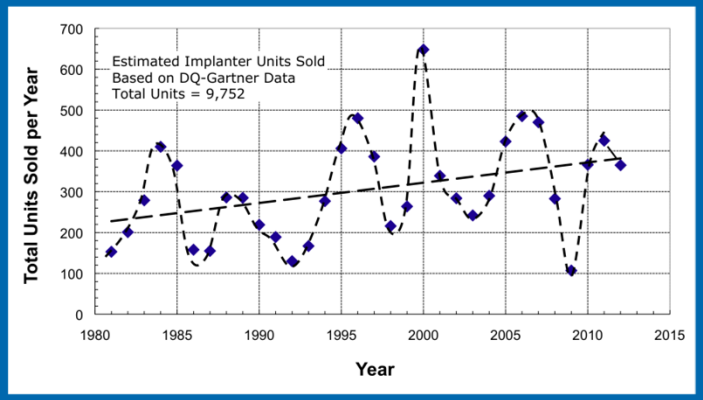
Metals

- Harden cutting tools.
- Reduce friction in metal parts.
- Biomaterials for implants.

Ceramics & Glasses

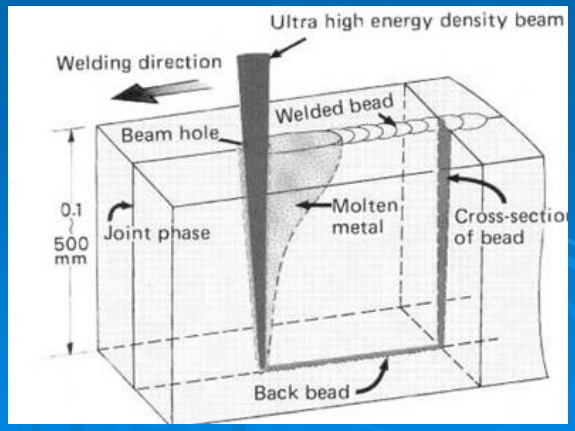
- Harden surfaces.
- Modify optics.

All digital electronics are dependent on ion implantation. A typical IC has 30-40 implants during fabrication.



Electron Beam Material Processing Applications

- Applications started in 1905
- Critical to automotive production
  - Welding & hardening of parts
  - Dissimilar metals – deep welds
  - Speed gears
- Precision cutting and drilling
  - 3000 holes/s at 0.55 mm diameter
- Recovery of refractory metals
- Typical industrial sectors
  - Automotive
  - Machine construction
  - Medical technology
  - Aerospace

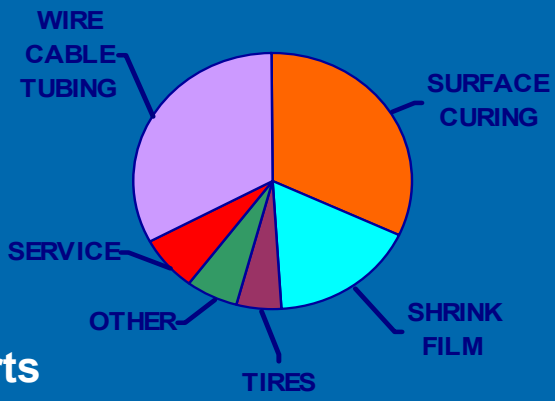


Many factory systems are fully automated.

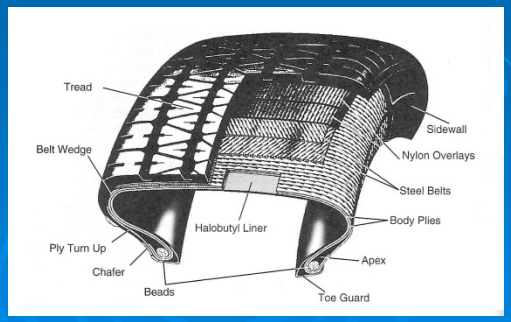
Electron Beam Irradiator Applications

S. Sabharwal – WEYB03

- **Cross linking of materials (largest application)**
  - **Wire & cable insulation – heat resistant**
  - **Heat shrink tubing**
  - **Heat shrinkable food packaging films**
  - **Closed cell polyethylene foams – auto & medical parts**
  - **Tire components**
  - **Curing of inks, coatings & adhesives – paper, wood, metals & plastics**
  - **Hydrogels for wound dressings**
  - **Sterilization of medical products (growing application) Syringes, catheters, gloves, surgical gowns and drapes, towels, bandages, tubing, fluid bags, labware, tubing, and absorbent**
- **Decontamination of food & medical device packaging**
- **Food and waste irradiation (largest potential applications)**



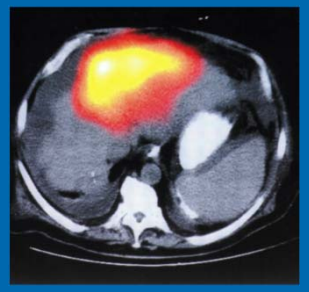
US$50B per year



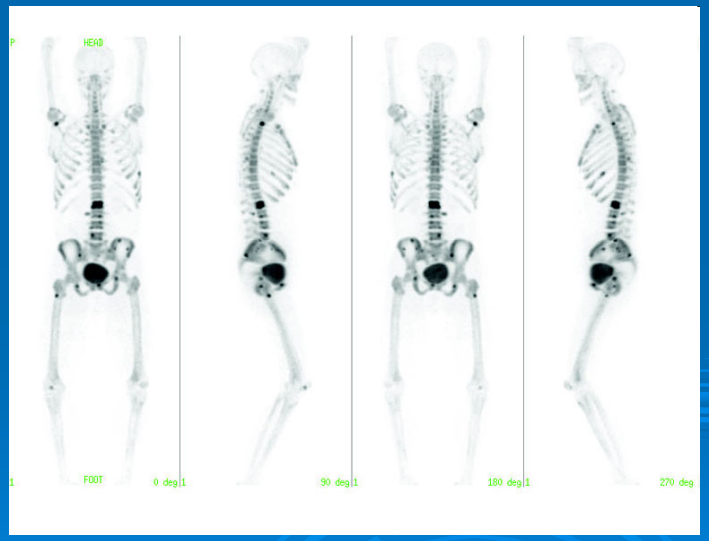
Radioisotope Applications

S. Lapi – THYBB2

- **Industrial – Gauging & Calibration**
  - Thickness monitoring
  - Moisture content determination



- **Medical – Diagnostics & Treatment**
  - Single Photon Emission CT: ^{123}I & ^{111}In (^{99m}Tc ??)
  - PET (Positron Emission Tomography): ^{18}F, ^{11}C, ^{15}O, ^{13}N, ^{64}Cu & ^{124}I
  - Brachytherapy: ^{125}I & ^{103}Pd



>50 accelerator-produced radioisotopes in routine use.

Ion Beam Analysis Applications

- **Application 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)

Applications

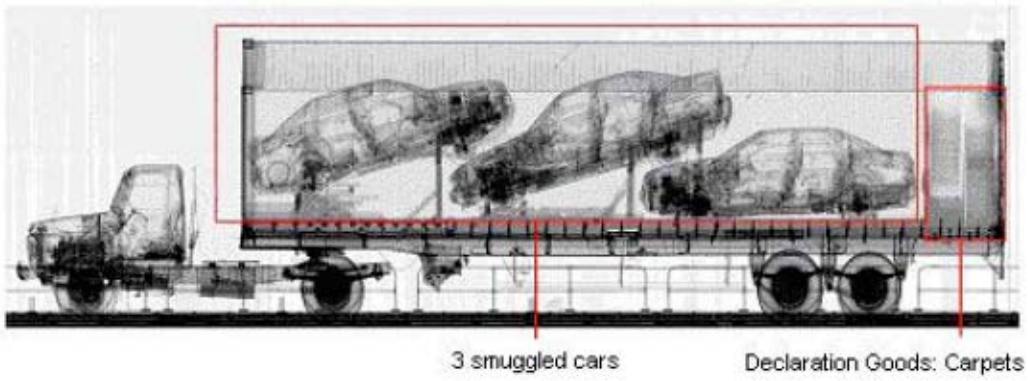
- ✓ Semiconductor quality
- ✓ Environmental monitoring
- ✓ Geological studies
- ✓ Oceanography studies
- ✓ Biomedical science
- ✓ Renewable energy

These applications are still widely used at many research labs.

High Energy X-Ray Inspection Applications

H. Chen – WEYB4

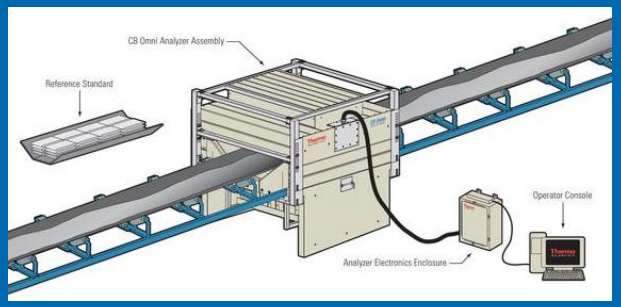
- Radiography of large castings – Original application that led to development of systems.
- Examination of rocket motors and munitions – Includes CT examinations systems.
- Port examination of containers & semi-trailers – Started as a security application and is now an import/export control tool.



Used by many countries for manifest verification.

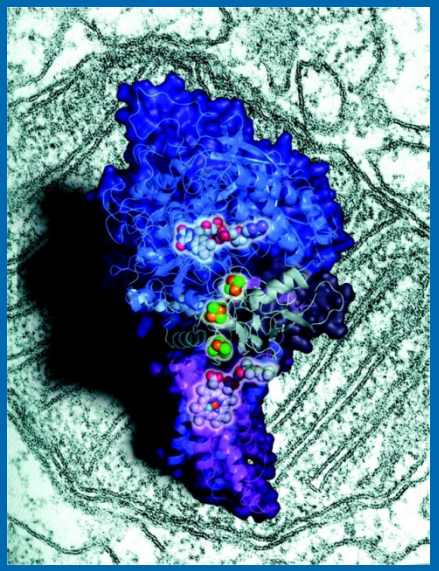
Neutron Generator Applications

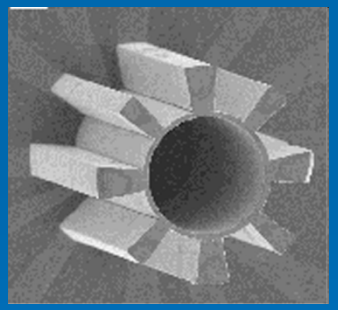
- **Geophysical Exploration** – Mineral detection and oil well borehole logging.
- **Bulk material analysis** – Includes gold, coal, cement and scrap metal on-line monitoring.
- **Gauging & radiography** – Materials inspection.
- **Neutron activation analysis** – Trace elements in biological and environmental areas.
- **Security** – Detection of contraband, high explosives, fissionable materials and chemical weapons agents.
- Now replacing many radioactive sources due to new US regulations on control of these sources.



Oil well logging is largest industrial application of these systems.

Synchrotron Radiation Applications





- **Application Techniques**
  - Fourier Transform infra-red spectroscopy
  - Infrared microspectroscopy
  - Circular dichroism
  - UV-VUV photo-electron spectroscopy (ESCA)
  - VUV-microspectroscopy
  - Powder & surface diffraction
  - Small angle & 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.)

- **Application Areas**
  - Semiconductors – lithography, material interface studies and production issues.
  - Chemical industry – Determine properties such as stress or texture of various materials produced and the chemical reactions themselves.
  - Biomedical – protein crystallography, molecular structures imaging, and molecular dynamics studies in tissue cells.

Industrial Accelerator Requirements

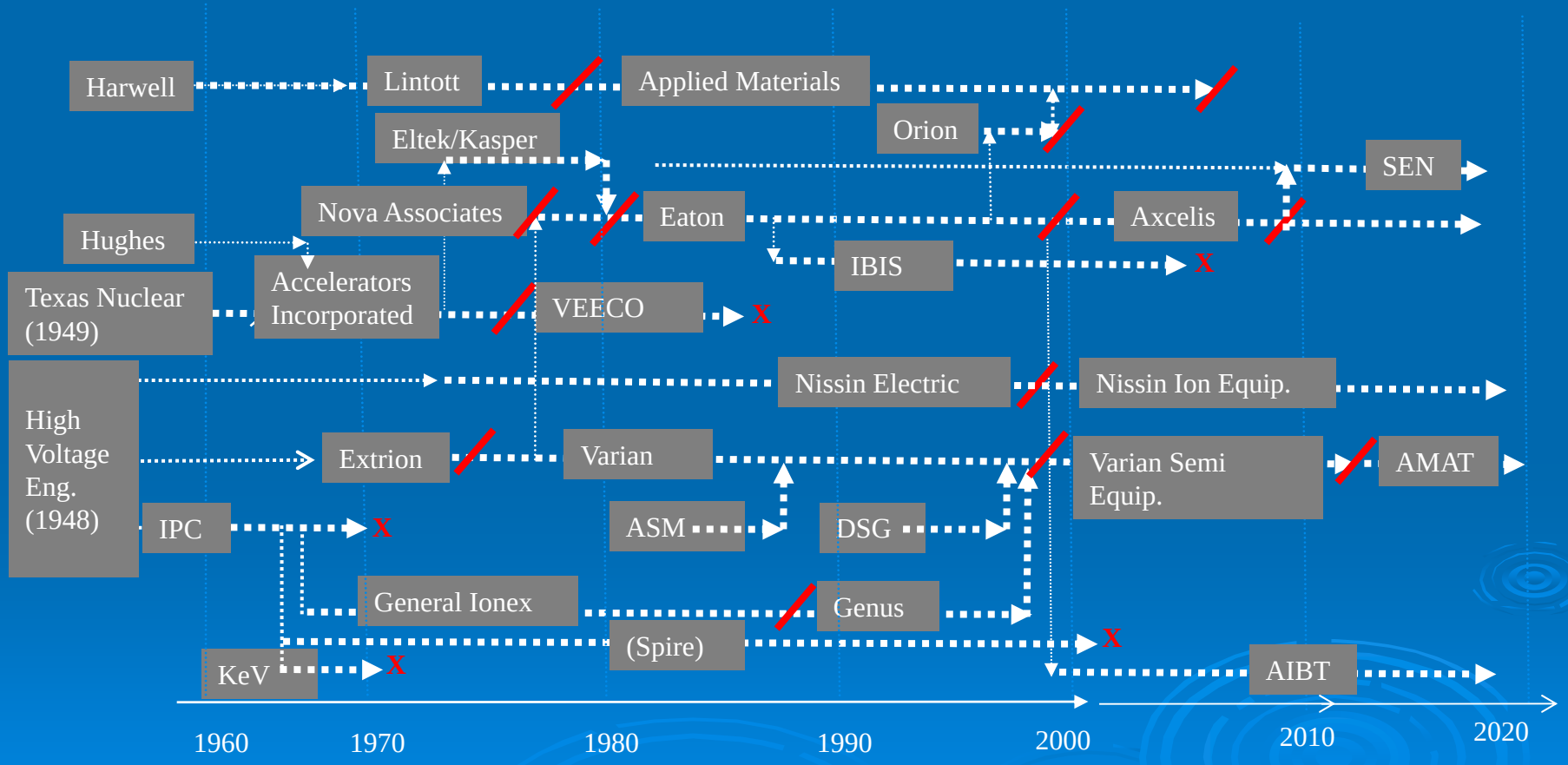
- The most important tool for industrial application is not the accelerator but the beam. A system must satisfy the beam specifications for a given application before it is a useful tool.
- Initial capital cost, operating cost, and reliability of the entire system play an important role in these “for-profit” applications.
- Users continuously seek lower total cost, so new technologies to increase the return on investment (ROI) are always being sought.
- New systems must be proven in an industrial setting before they gain widespread acceptance; significant market penetration can take many years after the introduction of a new accelerator technology.

  (Ion Implantation – ~1950 to 1970 for full acceptance and large market)

Major Implantation Companies: 1960-2013

A long history of new ventures, failures & mergers.

Courtesy Susan Felch – WEYB2

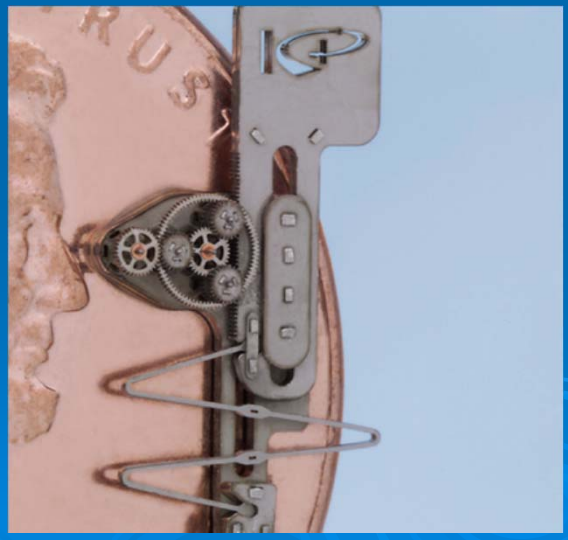


Other companies: mostly R&D and solar machines:
High Voltage Europa, Ulvac, National Electrostatics, Ion Beam Services, Intevac, Goldstone.

Future Technology & Applications

- **New Accelerator Technology**
  - Free Electron Laser (FEL) – *Next generation of synchrotron light?*
  - Superconducting Linacs & Cyclotrons – *Already in medical applications*
  - Fixed Field Alternating Gradient (FFAG) Cyclotron – *Several groups exploring their use in medical areas*

- **Future Industrial Applications**
  - Nanotechnology
  - Energy
  - Environmental



Superconducting Electron Linac Applications

Courtesy Terry Grimm – WEYB1

- Quarter wave electron guns
- Medical radioisotopes
- Free electron lasers
- High power X-ray sources
- Later: fast and thermal neutrons, Compton X-rays, photon activation analysis, wakefield accelerators, ultrafast electron microscopes, etc.

➢ Opportunities for commercial proton and heavy ion linacs being explored.

Conclusions

- Industrial Accelerators have an impact on all of our lives by
  - Enabling the manufacturing of products that we rely upon,
  - Protecting our health and improving medical diagnostics and treatment,
  - Improving our safety and security.

- The annual market for industrial accelerators is estimated (2010) to exceed US$1.5 Billion/year and is growing at >10% per year.

- There is the potential for increased impact in new areas, particularly in the fields of nanotechnology, environmental and energy.

- "Accelerator science is at a tremendously exciting period as we envision the next steps in energy, power, intensity and brightness, powered by new concepts and technologies. As history has shown, we can anticipate that those developments, motivated by Discovery Science, will have a substantial impact a***cross Physics and Society."*** Stuart Henderson, Fermilab, APS Mtg, May 3, 2011.