# INDUSTRIAL ACCELERATORS

Robert W. Hamm
R&M Technical Enterprises, Inc.
Pleasanton, California, USA

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# Presentation Outline

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

# Introduction to Industrial Accelerators

- "***Industrial Accelerators***" – All accelerators producing charged particle beams except for 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.

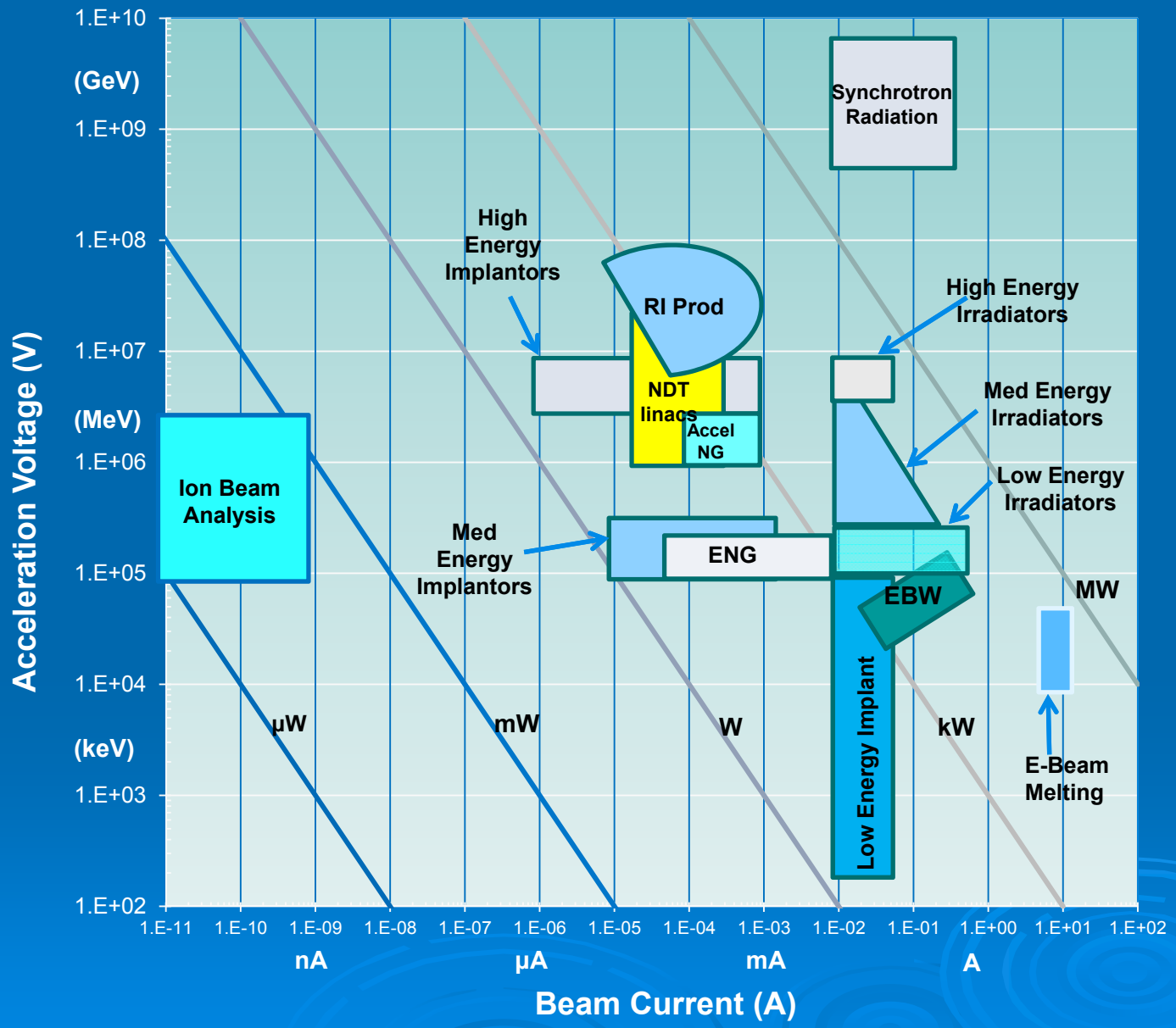
**Follows topics of recent book edited by authors on this subject.**

# 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 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 power to 50 kW.
  - **Ion linacs.** All use RFQs at 100 to 600 MHz. Energies from 1 to 70 MeV at beam currents 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 power 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 was originally developed in the 1930s for physics research.
- Soon after a new type of accelerator was invented someone recognized its potential for practical applications.
- Full market acceptance takes decades.
- Industrial accelerators have evolved into high quality products often tailored to a specific application with new technology developed just for these applications.

# Early Accelerator Technology Transfers

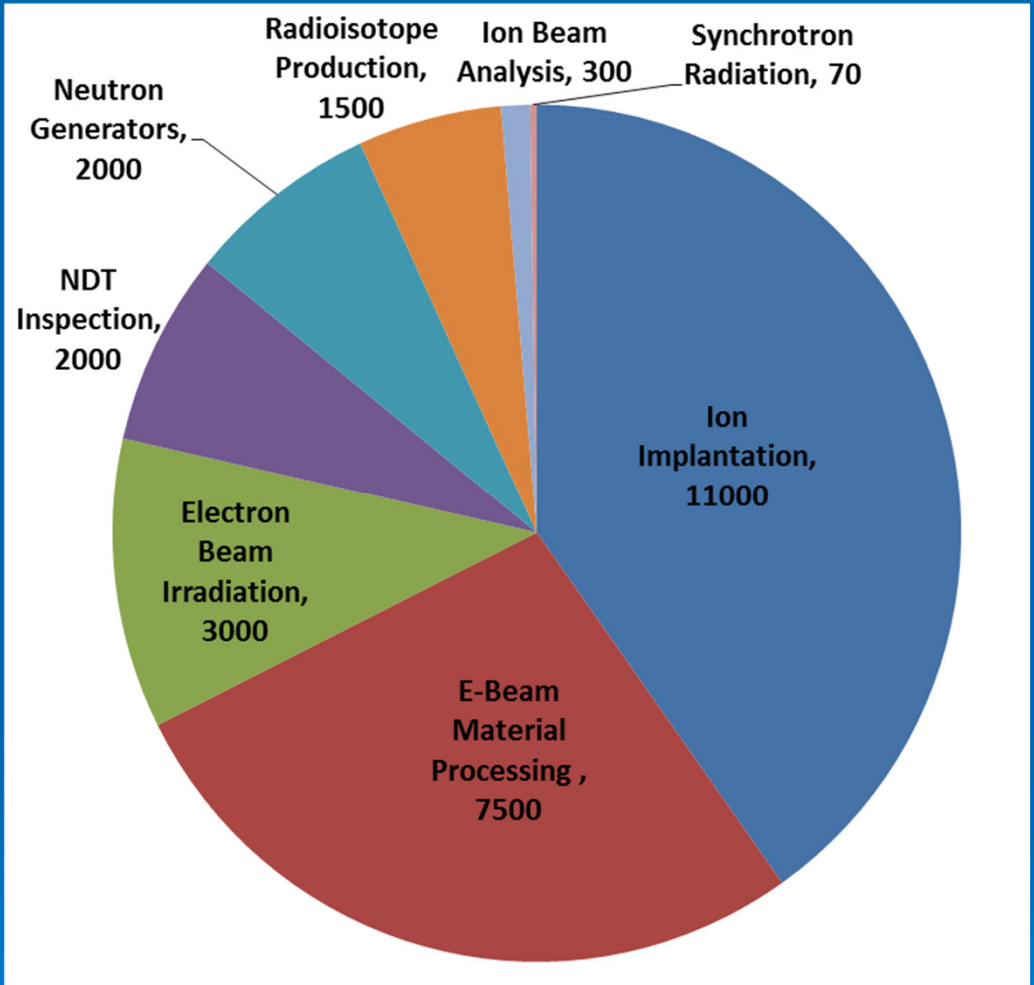
- Electron linacs – Varian collaboration with SLAC and later adoption of SCL from LANL for cancer therapy and later for industrial applications.

- 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



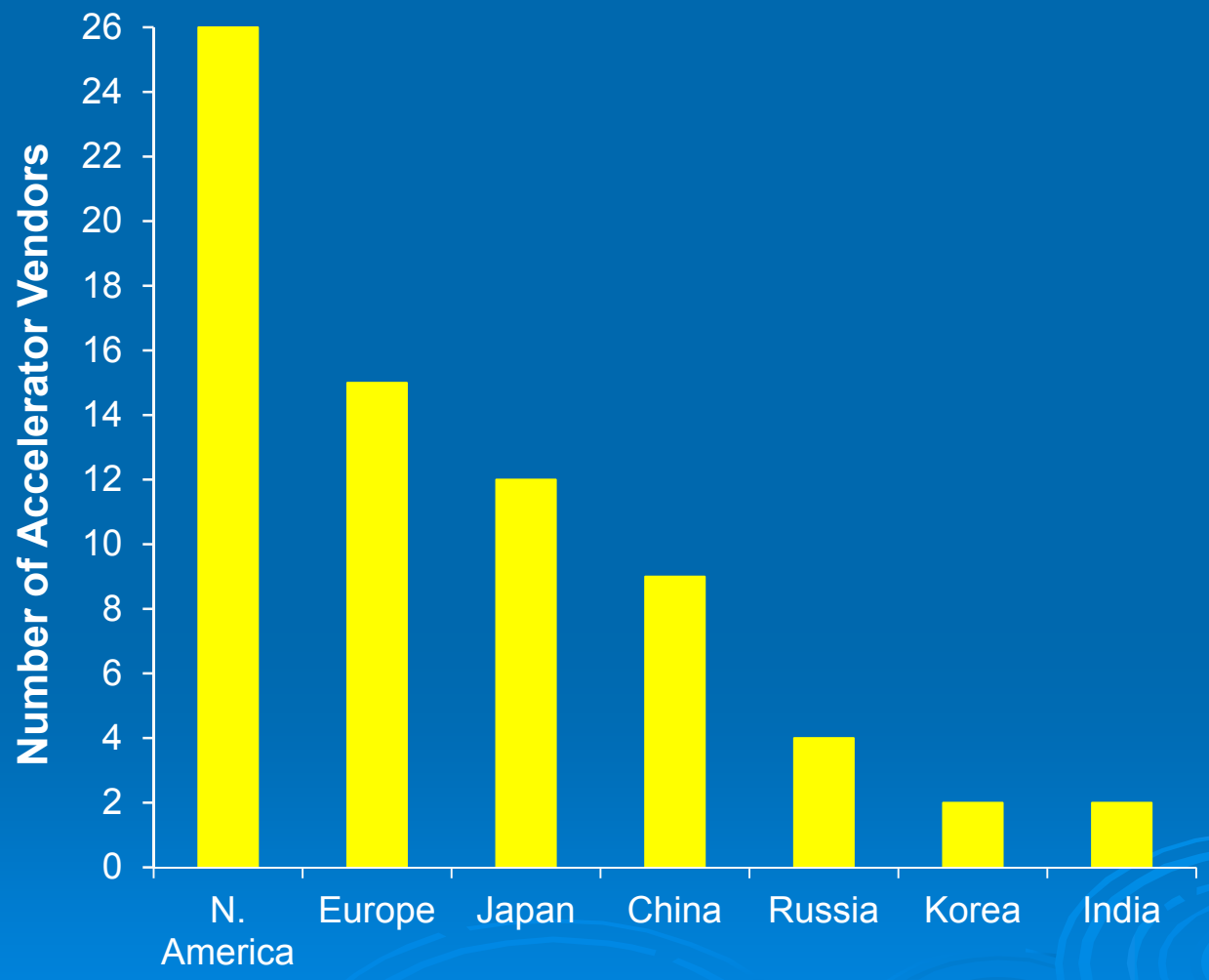

**Updated totals indicate that >27 000 systems have been sold and estimates are >20 000 still in operation today.**

**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

## 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.

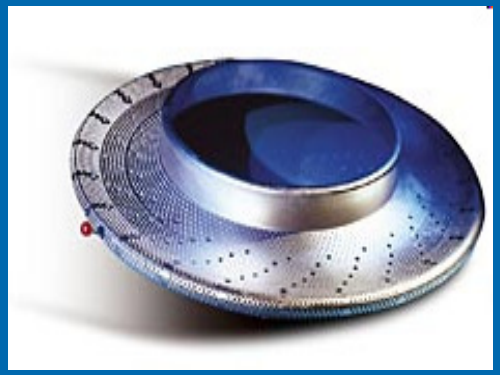
## Ceramics & Glasses

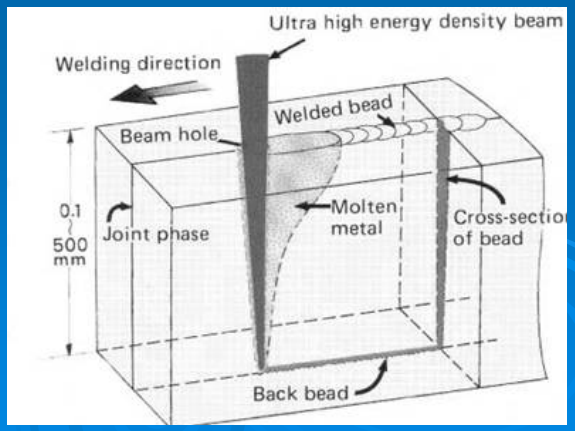
- Harden surfaces.
- Modify optics.

**All digital electronics are dependent on ion implantation. A typical IC has 25-30 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/sec at 0.55 mm diameter
- Recovery of refractory metals
- Typical industrial sectors
  - Automotive
  - Machine construction
  - Medical technology
  - Aerospace

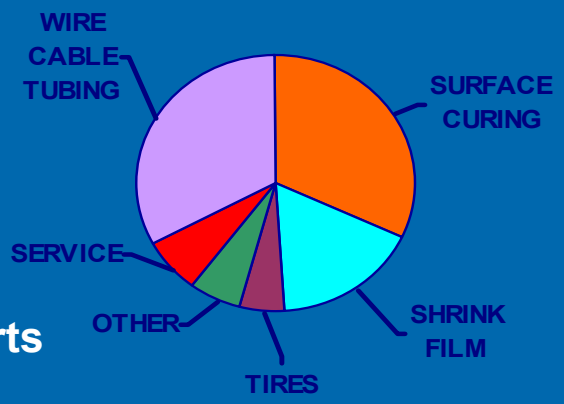


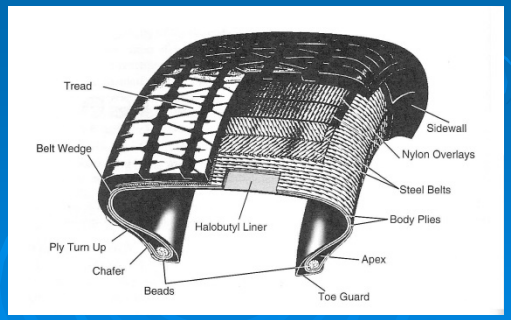

**Many factory systems are fully automated.**

# Electron Beam Irradiator Applications

- 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)

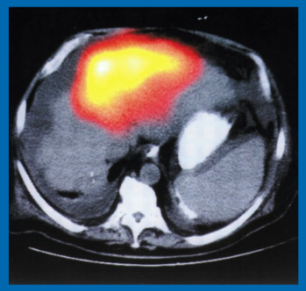



US$50B per year

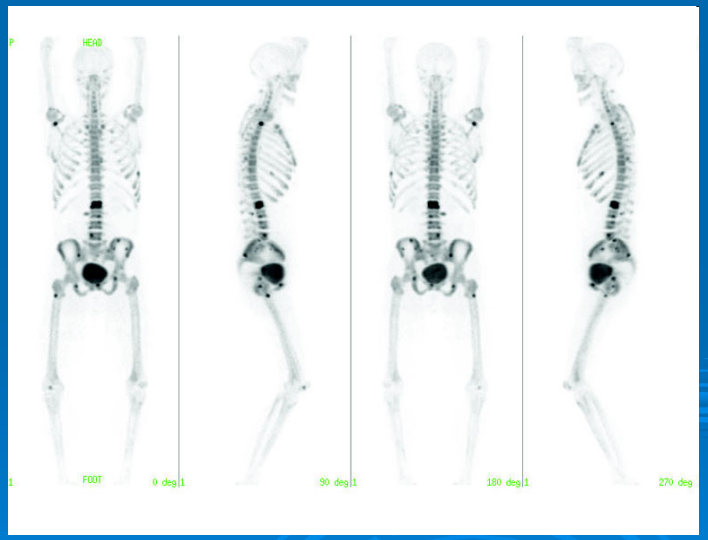


# Radioisotope Applications

- **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)

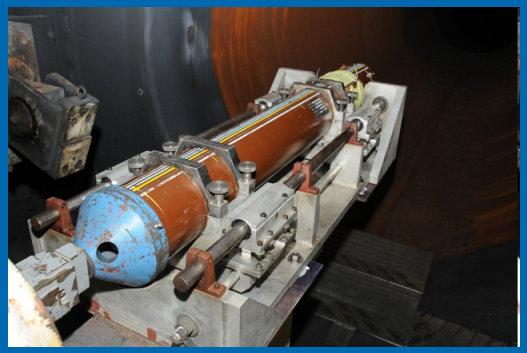
**Applications**

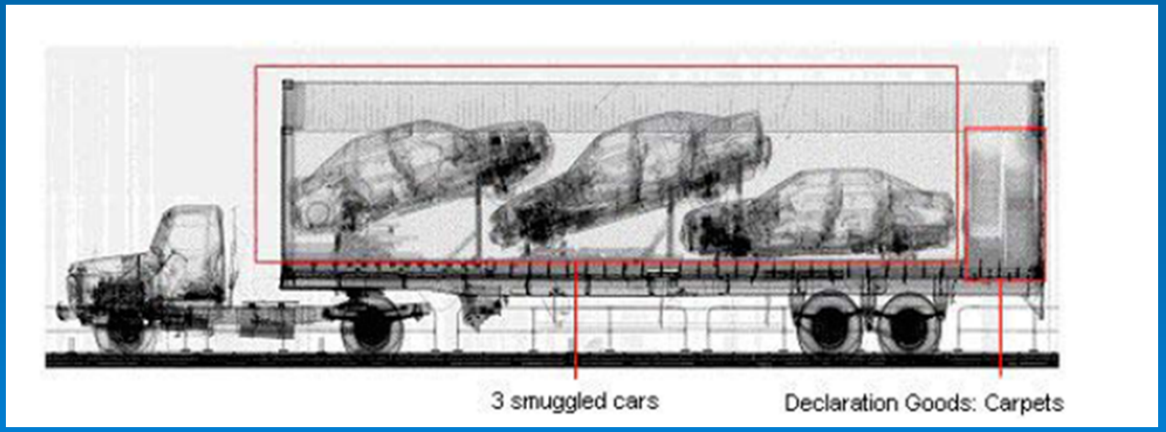
- ✓ Semiconductor quality
- ✓ Environmental monitoring
- ✓ Geological studies
- ✓ Oceanography studies
- ✓ Biomedical science
- ✓ Renewable energy


**These applications are still widely used at many research labs.**

# High Energy X-Ray Inspection Applications

- 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.

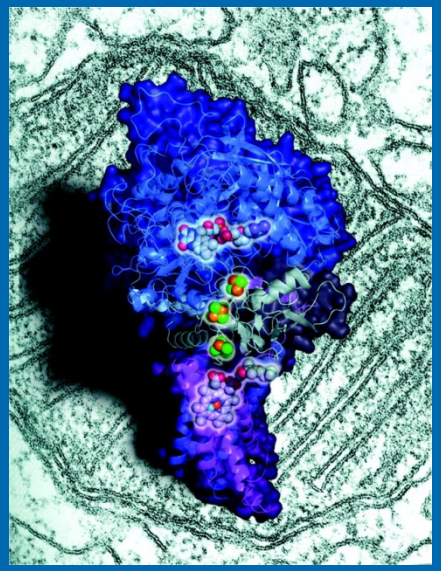


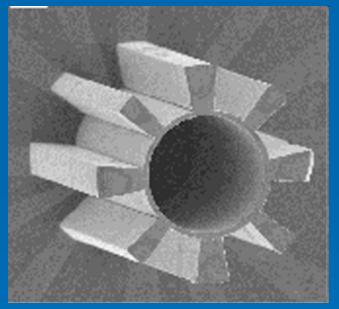



**Being adopted by many countries for manifest verification.**

# 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.

# Challenges for New Industrial Accelerators

- Increasing the beam intensity from the accelerators, particularly those required for energy production and environmental applications.
- Improving the performance of the accelerating structures to make them more compact and energy efficient.
- Making the systems more robust and reliable.
- Using new technology to decrease the costs.

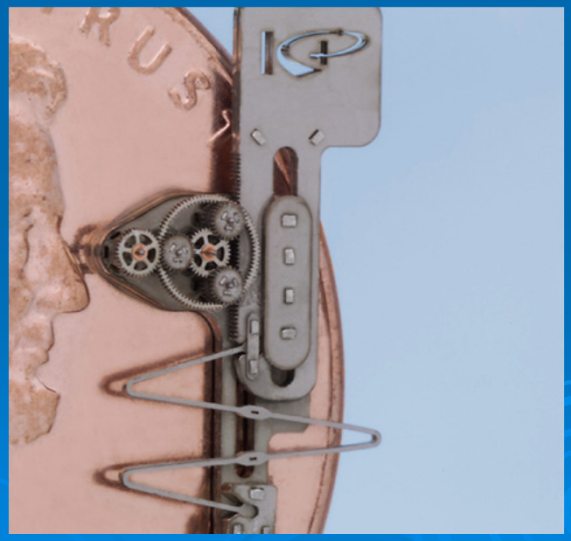
# Industrial Accelerator Requirements

- 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.
- The annual market for all medical and industrial accelerators described is estimated to now exceed US$3.0 Billion/ year and is growing at >10% per year (~90% of sales is concentrated in two industries).

# Future Technology & Applications

- **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*

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



# Conclusions

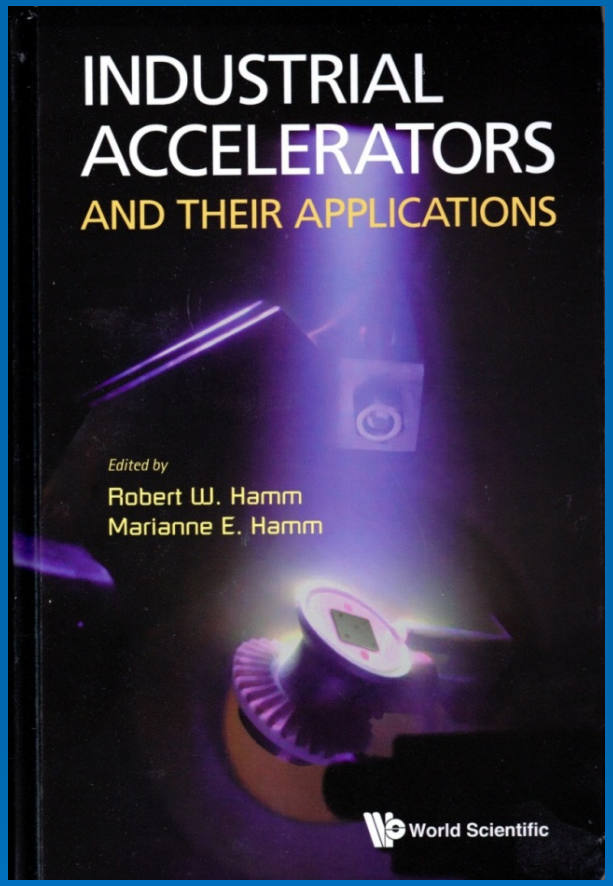
- Industrial Accelerators have an impact on all of our lives by
  - Enabling the manufacturing of products that we rely upon,
  - Protecting our health and improving medical diagnostics and treatment,
  - Improving our safety and security.

- There is the potential for increased impact in new areas, particularly in the fields of nanotechnology 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 Meeting, May 3, 2011.

# For More Details Beyond this Paper

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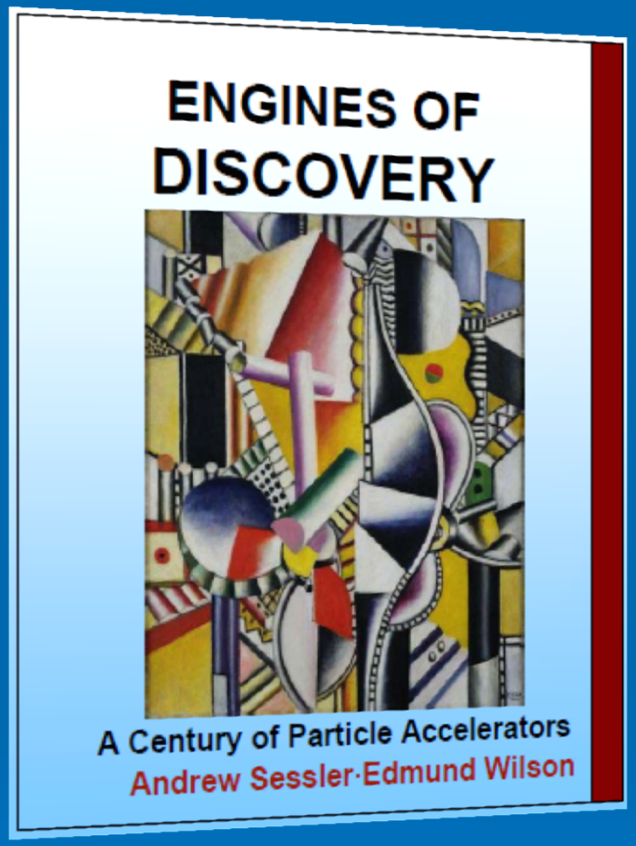


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