Applications of Accelerators

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Rutherford Appleton Laboratory and
University of Huddersfield
Outline

• Introduction to particle accelerators
  - at CERN
  - used for applications

• Summary of accelerator applications outside research

• Energy applications

• Medical applications:
  - cancer therapy
  - radioisotope production

• Industrial applications

• Environmental applications
Radioisotopes

- **Used for imaging:**
  - Positron Emission Tomography (PET)
  - Single Particle Emission Computed Tomography (SPECT)

- **Therapy:**
  - brachytherapy

- **Process:**
  - produce the isotope
  - extract and purify it
  - bind it to pharmaceutical
  - introduce into patient
  - decay used for imaging/therapy
Two main diagnostic radioisotopes:

PET
Two main diagnostic radioisotopes:

**Single photon emitters - SPECT**
Nuclear Imaging

• Requirements
  ▪ Must go where the want them
  ▪ Must emit photons that can be detected
  ▪ Half-life long enough for handling
  ▪ Short enough that they don’t last too long
  ▪ Manufacture costs not too high

• Used currently most often:
  ▪ SPECT: $^{99m}$Tc – 140 keV photons, 6 hour half-life
  ▪ PET: $^{18}$F – 2*511 keV photons, 2 hour half-life
NUCLEAR MEDICINE PROCEDURES
USA 2008 TOTAL 17.3 million
**99mTc Production**

- Made in (test) nuclear reactors
  - $^{99}$Mo produced by fission of HE $^{235}$U
  - ~6% of fission reactions
  - Mo is extracted in hot cells
  - Purified
  - Loaded into a “generator”
  - $^{99m}$Tc produced from Mo decay, half-life 66 hours
• Until recently, done in 5 aging reactors

<table>
<thead>
<tr>
<th>Reactor</th>
<th>Location</th>
<th>Date of first commissioning</th>
<th>Power (MW)</th>
<th>Operational days per year</th>
<th>Capacity (% of European needs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NRU</td>
<td>Chalk River, Canada</td>
<td>1957</td>
<td>135</td>
<td>270</td>
<td>N/A</td>
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<tr>
<td>HFR</td>
<td>Petten, the Netherlands</td>
<td>1961</td>
<td>45</td>
<td>280</td>
<td>&gt;100</td>
</tr>
<tr>
<td>BR2</td>
<td>Mol, Belgium</td>
<td>1961</td>
<td>100</td>
<td>140</td>
<td>&gt;100 when operating</td>
</tr>
<tr>
<td>OSIRIS</td>
<td>Saclay, France</td>
<td>1966</td>
<td>70</td>
<td>180</td>
<td>~25 when operating</td>
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<tr>
<td>SAFARI</td>
<td>Pelindaba, South Africa</td>
<td>1965</td>
<td>20</td>
<td>310</td>
<td>N/A</td>
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<tr>
<td>OPAL *</td>
<td>Lucas Heights, Australia</td>
<td>2006</td>
<td>20</td>
<td>340</td>
<td>N/A</td>
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<tr>
<td>MARIA †</td>
<td>Swierk, Poland</td>
<td>1974</td>
<td>30</td>
<td>160</td>
<td>~10 when operating</td>
</tr>
<tr>
<td>LVR-15 †</td>
<td>Rez, Czech Republic</td>
<td>1957</td>
<td>10</td>
<td>210</td>
<td>~10</td>
</tr>
</tbody>
</table>

* Not yet exporting $^{99}$Mo  
† Began international supply of $^{99}$Mo in 2010

• Variety of radiopharmaceuticals produced in hospital
Well-known $^{99m}$Tc problems due to (old) reactor production

- Moly crisis in 2008/9
- Potential shortage in ≥2016 due NRU closure & LEU

Various alternative production methods proposed, including accelerators

BNMS & STFC Report, December 2014
Particle accelerators

**Proton accelerators**
- 100Mo target
  - Reaction: 100Mo(p,2n)99mTc

**Heavy nucleus target**
- 98Mo target
  - Reaction: 98Mo(n,γ)99Mo
- 235U target
  - Reaction: 235U(n,f)99Mo

**Bremsstrahlung target**
- 238U target
  - Reaction: 238U(γ,f)99Mo
- 100Mo target
  - Reaction: 100Mo(γ,n)99Mo
  - Reaction: 100Mo(n,2n)99Mo

**Carbon target**
- 100Mo target
  - Reaction: 100Mo(n,2n)99Mo

**Deuteron accelerators**

**Electron accelerators**

**Primary particle**

**Secondary particle**

Nuclear Energy Agency: direct production $^{100}\text{Mo}(p,2n)^{99}\text{mTc}$

Short term: <2017
Med term: 2017-2025
Long term: >2025
• Tests done, mainly in Canada:
  - direct production using cyclotrons
  - photo-production using linacs

TR19: 14-19 MeV
~200 μA
Pop^n ~2.5M

TR24: 24 MeV, ~500 μA, pop^n ~4.5M
Accelerator Production

35 MeV, 2 kW test
Accelerator Production

• Tests done, mainly in Canada:
  - direct production using cyclotrons
  - photo-production using linacs

• Technically looks feasible, but needs to be cost effective
• Pretty much all produced using a cyclotron
• Main isotope: $^{18}$F
• Reaction: $^{18}$O(p,n)$^{18}$F
• $^{18}$O enriched in water
<table>
<thead>
<tr>
<th>Company</th>
<th>Country</th>
<th>No of models</th>
<th>Lowest energy model (MeV)</th>
<th>Highest energy model (MeV)</th>
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</thead>
<tbody>
<tr>
<td>IBA</td>
<td>Belgium</td>
<td>7</td>
<td>3</td>
<td>235</td>
</tr>
<tr>
<td>General Electric</td>
<td>Sweden</td>
<td>2</td>
<td>11</td>
<td>16</td>
</tr>
<tr>
<td>Siemens</td>
<td>USA</td>
<td>1</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>ACSI</td>
<td>Canada</td>
<td>4</td>
<td>14</td>
<td>30</td>
</tr>
<tr>
<td>Best Medical</td>
<td>USA</td>
<td>4</td>
<td>14</td>
<td>70</td>
</tr>
<tr>
<td>KRIA</td>
<td>S Korea</td>
<td>2</td>
<td>13</td>
<td>30</td>
</tr>
<tr>
<td>Sumitomo</td>
<td>Japan</td>
<td>4</td>
<td>7</td>
<td>18</td>
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<tr>
<td>EuroMeV</td>
<td>France</td>
<td>1</td>
<td>12</td>
<td></td>
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<tr>
<td>Efrimov Inst.</td>
<td>Russia</td>
<td>1</td>
<td>18</td>
<td></td>
</tr>
<tr>
<td>CIAE</td>
<td>China</td>
<td>3</td>
<td>14</td>
<td>100</td>
</tr>
</tbody>
</table>

550 in 2007
Growing at ~50/year
Variety of cyclotrons used with variety of energies:

- 30 MeV, IBA
- 14-19 MeV
- 11 MeV, Siemens
• Most widely used pharmaceutical by far:

2-[18F]fluoro-2-deoxy-D-glucose (FDG)

• Usually produced centrally and shipped to hospital

• Much interest in shorter lived isotopes:
  - 11C: ~20 min – C in all biological molecules
  - 13N: ~10 min
  - 15O: ~2 min

• Must be produced locally

• Needs compact/cheap accelerators
• Replace $^{99m}\text{Tc}$ with other radioisotopes

• PET, e.g. $^{18}\text{F}$, $^{82}\text{Rb}$, $^{68}\text{Ga}$, ?

• Other SPECT isotopes, e.g. $^{123}\text{I}$, $^{87m}\text{Sr}$, $^{113m}\text{In}$, $^{81m}\text{Kr}$, etc

• Potential problem: increased production costs

• Needs more cost effective accelerator production
• Mainly reactor produced
• Supply can be a problem

Courtesy: Uli Koester

Therapeutic Radioisotopes

![Graph showing activity levels over years for 131I, 90Y, and 177Lu](chart)

Federal Office of Public Health, Bern, Switzerland
Mainly reactor produced

Supply can be a problem

Some can be made by accelerator:
- $^{177}\text{Lu}$
- $^{153}\text{Sm}$

Some interesting isotopes need $\alpha$:
$^{211}\text{At}$, $^{67}\text{Cu}$, $^{47}\text{Sc}$

Need to be cost effective:
- right beam
- right energy
- high beam current
$^{209}\text{Bi}(\alpha,2n)^{211}\text{At}$

$^{209}\text{Bi}(\alpha,3n)^{210}\text{At}$
Developments to tackle issues

- Compact cyclotrons for patient-sized doses in hospitals
- For $^{18}$F (2 hrs), but also $^{11}$C (20 mins) and $^{15}$O (2 mins)

ABT Molecular
7.5 MeV, 5μA
Developments to tackle issues

- Compact cyclotrons for patient-sized doses in hospitals
- For $^{18}$F (2 hrs), but also $^{11}$C (20 mins) and $^{15}$O (2 mins)
- AMIT (CIEMAT, Spain, plus collaborators)

4T magnet, based on CERN work
>8.5 MeV, >10 $\mu$A
Tests soon
Developments to tackle issues

- Compact tandem electrostatic accelerator: The Oniac (Siemens)
- Aim: 10 MeV, ~2 mA

Tested to >100 μA

Courtesy: Siemens
Developments to tackle issues

- Non-scaling FFAG (PIP)
- Aim: 0.075 to 28 MeV, ~20 mA protons and α
- Possibility of internal target
Radioisotopes Conclusions

• There may or may not be a moly problem!

• Existing and new PET isotopes have a lot of potential

• Therapeutic isotopes are a mess:
  - they have a lot of potential
  - supply can be a problem
  - accelerators can help, but are somewhat limited by current technology

• Several technologies being developed
• Ion implantation
• Ion beam analysis
• Electron beams for industrial applications
• Electron beams for environmental applications
Industrial Applications

- **Ion implantation**: an energetic process by which impurity atoms are introduced into the *near surface* of a material to change its *electrical, optical or materials* properties:
  - Doping in semiconductors
  - Device isolation in integrated circuits
  - Compound synthesis
  - Defect Engineering
  - Waveguides and optical devices
  - Anti-fouling
  - Wear resistance in metals - hip replacement

- Beam energy: typically 10 to 500 keV, but up to 5 MeV
- Beam current: 10 μA to 30 mA
- Electrostatic accelerators
- >10000 in operation
Ion beam analysis: determining material structure and composition >1500
Variety of techniques:

- Accelerator Mass Spectrometry (AMS)
- Particle Induced X-ray Emission (PIXE)
- Rutherford Back Scattering (RBS)
- Elastic Recoil Detection Analysis (ERD)
- Particle Induced Gamma ray Emission (PIGE)
- Nuclear Resonance Reaction Analysis (NRA)
- Charged Particle Activation Analysis (CPA)
PIXE-PIGE analysis of the 15th century stained glass panel from St. Denis basilica (12C AD).

Inks in Galileo’s manuscripts (Florence National Library) analysed by external PIXE.

Micro-PIXE and – PIGE analysis of the gold threads of a Renaissance embroidery based on a cartoon by Raffaellino del Garbo.

Differential PIXE and PIGE analysis of the Madonna dei Fusi by Leonardo.
• Many applications

• Tend to be classed as
  - very low energy: 10 to 300 keV
  - low energy: 300 keV to 10 MeV

• Above 10 MeV causes activation

• Overlap in applications
Low Energy Electron Beams

>10000 accelerators:

< 5 MeV ~ electrostatic, mainly industrial applications

5 - 10 MeV ~ RF linacs for security (& medical)
~~ rhodatron for high currents for industry

300 keV Electron Crosslinking

1 MeV for water treatment

10 MeV IBA Rhodotron
### Effects of Electron Beam Interaction

#### Thermal Processes
- Heat Production
  - Vacuum
    - Evaporation
    - Melting
    - Welding / Joining
    - Hardening
    - Micro-structuring

#### Non-thermal Processes
- Chemical Reactions
  - Atmosphere
    - Curing
    - Crosslinking
    - Drying print-inks
    - Surface modification (Grafting)

- Biocidal Effects
  - Atmosphere
    - Disinfection of animal feed
    - Seed treatment
    - Sterilisation of products
    - Sterile packaging
    - Inactivation of pharma waste

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**Courtesy Frank-Holm Roegner**
Very Low Energy Electrons

Power [W]

Power density [W/cm²]

Curing, Cross-linking, Sterilization 20 – 10,000 keV
Evaporation 10 – 40 keV
Melting 10 – 80 keV
Welding, Hardening 15 – 180 keV
Structuring 20 – 150 keV
EBID, EBIE 20 – 50 keV

Courtesy Frank-Holm Roegner
Sterilisation of bottles
Example: Hitachi Zosen Corp., Japan

Before filling the ready formed 500 ml PET bottles are sterilized by being irradiated from both the inside and outside using AEB - low-energy electron beams 150 keV (outside), and 100-125 keV (inside). Process time 2-4 seconds per bottle, with 25 kGy dosage.

Standard production lines for filling 500-ml PET bottles at a rate of 600 bottles per minute.

Courtesy Frank-Holm Roegner
Very Low Energy Electrons

Sterilisation of bottles
Example: Hitachi Zosen Corp., Japan

Sterilization by electron beam irradiation
(illustration of device interior)

Filling with beverage

Courtesy Frank-Holm Roegner
Very Low Energy Electrons

Treatment of seeds
Example: Frauenhofer FEP

Dose distribution

Courtesy Andre Weidauer
Curing of lacquer on furniture
Example: Scannery Holztechnik GmbH, Falkenhagen/Germany

Continuous transportation of furniture sheets

Lacquered wood floor for industrial use

Courtesy Frank-Holm Roegner
Curing of lacquer on furniture
Example: Scannery Holztechnik GmbH, Falkenhagen/Germany

Courtesy Frank-Holm Roegner
## Low Energy Electrons

<table>
<thead>
<tr>
<th>Market segment</th>
<th>Typical energy</th>
<th>Electron penetration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface curing</td>
<td>80 – 300 keV</td>
<td>0.4 mm</td>
</tr>
<tr>
<td>Shrink film</td>
<td>300-800 keV</td>
<td>2 mm</td>
</tr>
<tr>
<td>Wire &amp; Cable</td>
<td>0.4 – 3 MeV</td>
<td>11 mm</td>
</tr>
<tr>
<td>Sterilization</td>
<td>4 – 10 MeV</td>
<td>38 mm</td>
</tr>
<tr>
<td>Food</td>
<td>4 – 10 MeV</td>
<td>38 mm</td>
</tr>
<tr>
<td>Composites (carbon fiber)</td>
<td>10 MeV</td>
<td>24 mm or less</td>
</tr>
<tr>
<td>Flue gas</td>
<td>300 – 1000 keV</td>
<td>120 cm to 3m</td>
</tr>
<tr>
<td>Wastewater</td>
<td>1 MeV</td>
<td>2 mm</td>
</tr>
<tr>
<td>Biological sludge</td>
<td>1 – 10 MeV</td>
<td>2 mm do 30mm</td>
</tr>
</tbody>
</table>

*Courtesy Andrzej Chmielewski*
## Low Energy Electrons

<table>
<thead>
<tr>
<th>Application</th>
<th>Dose range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medical – diagnostic</td>
<td>10 – 100 mGy</td>
</tr>
<tr>
<td>Medical – therapy</td>
<td>1 – 10 Gy</td>
</tr>
<tr>
<td>Industrial – food and agriculture</td>
<td>0.1 – 10 kGy, or more</td>
</tr>
<tr>
<td>Industrial - sterilization</td>
<td>10 – 30 kGy</td>
</tr>
<tr>
<td>Industrial – materials modification</td>
<td>50 – 100 kGy, or more</td>
</tr>
<tr>
<td>Flue gas treatment (SOx, NOx, VOC)</td>
<td>2-10 kGy</td>
</tr>
<tr>
<td>Wastewater</td>
<td>1 to 2 kGy</td>
</tr>
<tr>
<td>Biological sludge</td>
<td>2 to 3 kGy</td>
</tr>
</tbody>
</table>

*Courtesy Andrzej Chmielewski*
Low Energy Electrons

- SURFACE CURING
- WIRE CABLE TUBING
- SERVICE
- SHRINK FILM
- TIRES
- OTHER

Courtesy Andrzej Chmielewski
Low Energy Electrons

Courtesy Grazyna Przybytniak
**Flue Gas Treatment**

- Removal of NOx, SOx and VOC
  - Avoid acid rain

- Current technique:
  - chemical
  - bi-product is gypsum

- Electron beam technique:
~4 pilot plants
Not used in production yet
Cargo Ships

- Removal of NOx and SOx from diesel engines
- Treatment of ballast water transported around the world
• Currently, 1.9B people use either an unimproved water source or an improved water source that is faecally contaminated

• In Africa, it is estimated that 15-20% of deaths are water related

• First two targets of the United Nations Sustainable Development Goal 6:
  - 6.1: By 2030, achieve universal and equitable access to safe and affordable drinking water for all
  - 6.2: By 2030, achieve access to adequate and equitable sanitation and hygiene for all and end open defecation, paying special attention to the needs of women and girls and those in vulnerable situations

• Can accelerators help?
Water Treatment

• Basic process:
  - $e^-$ react with water to produce active radicals: $\text{OH}^*$, $\text{H}^*$, $\text{H}_2\text{O}_2$
  - radicals react with contaminants to remove in various ways
  - very similar to cancer therapy!

• Already used industrially:
  - Wastewater from Textile Dyeing Companies
  - Wastewater from Papermill
  - Leachate from Sanitary Landfill
  - Wastewater containing Heavy metals ($\text{Cd, Hg, Pb, Cr}^{+6}$)
  - Re-use of effluent from sewage plant
  - Remediation of contaminated water (PCB, Explosives)
  - Contaminated Underground water
  - Drinking water
Water Treatment

Wastewater Treatment Facility in Daegu Dyeing Industrial Complex

120 companies, 80000m³ of waste water per day

Location of Pilot Plant

Courtesy: B. Han
Water Treatment

Influent → Chemical Treatment → Primary Aeration → Sedimentation → 2nd Aeration → Sedimentation → Reservoir

Effluent

Process Flow of Existing Wastewater Treatment Facility

Thickening → dewatering → Landfill

Courtesy: B. Han
Water Treatment

80,000 m³/day

Main facility

1000 m³/day

Tower Type Biological System

1,000 m³/day

Reservoir

Influent

E-fluent

E-Beam Irradiation

Courtesy: B.Han
Effect of electron-beam treatment on biological treatment of dyeing wastewater:

- **a** - kinetics of biotreatment of irradiated \( 1 \) and unirradiated \( 2 \) wastewater;
- **b** - absorbed dose effect on combined electron-beam/biological treatment.

**Courtesy:** B.Han
Water Treatment

Commercial plant
10000m³/day
1 MeV, 400 kW

Courtesy: B. Han
Biological Sludge Treatment

• Called many things: what’s left over after waste water treatment

• Highly contaminated:
  - difficult to deal with everywhere
  - major cause of sickness and death in developing world

• Developed disposal old:
  - dumped at sea
  - discharged in surface water

• Now:
  - anaerobic digestion → fertiliser
  - incineration (some times for power production)
  - landfill
Biological Sludge Treatment

Wastewater treatment plant (WWTP)

- primary treatment
- biological treatment
- secondary sedimentation

Sludge

Biogas production plant

- anaerobic fermentation
- hydrolysis

- co-generation
- biogas

- heat electricity

- fertilizer

purified water

eb

 Courtesy: Urszula Gryczka
Biological Sludge Treatment

- Environmentally friendly
- Disposal of problematic waste
- Bio-gas production
  - 60% more efficient
  - smaller facility
  - faster
- Production of microbiologically safe organic fertiliser
- Technology can be used anywhere with sufficient biomass, no need for external power
- Pilot plant under development in Poland
- Proposal submitted for studies in Ghana and Uganda

Courtesy: Urszula Gryczka
Industrial Conclusions

• Industrial applications are very important......

• ......but not very glamourous!

• Environmental applications:
  - have a lot of potential
  - but need to be cost-effective
  - big companies need to be convinced of the benefits

• For the developing world:
  - lots of potential
  - main focus needs to be on developing simple, cheap systems
  - must meet in the local needs
  - outreach is just as important
General Conclusions

• Accelerators are v. important for things other than making Higgses
• They are already used extensively
• But new applications are still being developed
• Technology for research can and is playing a role
• But the requirements are different
• Technology needs to be adapted to meet the needs
• Not vice versa