Applications of Accelerators

CERN Introductory Accelerator School
Constanta, Romania, 2018.

Dr. Suzie Sheehy
Royal Society University Research Fellow
John Adams Institute for Accelerator Science
University of Oxford
• “A beam of particles is a very useful tool...”

-Accelerators for Americas Future Report, pp. 4, DoE, USA, 2011

There are roughly 35,000 accelerators in the world (Above 1 MeV...)
Outline

1. Medical imaging and treatment
2. Industrial uses of accelerators
3. Synchrotron light sources
4. Neutron sources
5. Energy and security applications
6. Historical & cultural applications
1. Medical Applications
• Around 1/3 of people in the will die from cancer...
• But diagnosis is no longer a death sentence!

Patients cured by the major cancer treatment modalities

- Radiotherapy: 40%
- Surgery: 49%
- Chemotherapy: 11%
  - alone
  - with surgery
  - with radiotherapy

Reference
Cancer Services Collaborative 2002
www.nhs.uk/npat
X-ray radiotherapy

Linac

Foil to produce x-rays

Collimation system

Image: copyright Varian medical systems
Charged Particle Therapy

• Greater dose where needed
• Less morbidity for healthy tissue
• Less damage to vital organs

Bragg Peak
Energy loss in materials

The relativistic version of the formula reads:

\[ -\frac{dE}{dx} = \frac{4\pi}{m_e c^2} \cdot \frac{n z^2}{E} \cdot \frac{e^2}{4\pi \varepsilon_0} \cdot \ln \left( \frac{2 m_e c^2 \beta^2}{e^2} \right) \cdot \ln \left( \frac{2 m_e v^2}{I} \right) \]

where

\[ \beta = \frac{v}{c} \]
\[ v \text{ velocity of the particle} \]
\[ E \text{ energy of the particle} \]
\[ x \text{ distance travelled by the particle} \]
\[ c \text{ speed of light} \]
\[ z e \text{ particle charge} \]
\[ e \text{ charge of the electron} \]
\[ m_e \text{ rest mass of the electron} \]
\[ n \text{ electron density of the target} \]
\[ I \text{ mean excitation potential of the target} \]
\[ \varepsilon_0 \text{ vacuum permittivity} \]

High speed -> small energy loss
Low speed -> high energy loss
Proton therapy

— “Hadron therapy” = Protons and light ions

• Used to treat localised cancers
• Less morbidity for healthy tissue
• Less damage to vital organs
• Particularly for childhood cancers
A few developments

Spot Scanning
Proton Radiography
Gantries
FFAG Accelerators
Dielectric Wall Accelerators
Laser Plasma Accelerators

HEP community can contribute accelerators AND other expertise!
Radioisotope production

- Accelerators (compact cyclotrons or linacs) are used to produce radio-isotopes for medical imaging.
- 7-11MeV protons for short-lived isotopes for imaging
- 70-100MeV or higher for longer lived isotopes

- Positron emission tomography (PET) uses Fluorine-18, half life of ~110 min
- Fluorodeoxyglucose or FDG carries the F18 to areas of high metabolic activity
- 90% of PET scans are in clinical oncology
Radiopharmaceuticals

$p, d, 3\text{He}, 4\text{He}$ beams

Isotopes used for PET, SPECT and Brachytherapy etc...

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Isotope</th>
<th>Isotope</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actinium-225</td>
<td>Fluorine-18</td>
<td>Oxygen-15</td>
</tr>
<tr>
<td>Arsenic-73</td>
<td>Gallium-67</td>
<td>Palladium-103</td>
</tr>
<tr>
<td>Arsenic-74</td>
<td>Germanium-68</td>
<td>Sodium-22</td>
</tr>
<tr>
<td>Astatine-211</td>
<td>Indium-110</td>
<td>Strontium-82</td>
</tr>
<tr>
<td>Beryllium-7</td>
<td>Indium-111</td>
<td>Technetium-94m</td>
</tr>
<tr>
<td>Bismuth-213</td>
<td>Indium-114m</td>
<td>Thallium-201</td>
</tr>
<tr>
<td>Bromine-75</td>
<td>Iodine-120g</td>
<td>Tungsten-178</td>
</tr>
<tr>
<td>Bromine-76</td>
<td>Iodine-121</td>
<td>Vanadium-48</td>
</tr>
<tr>
<td>Bromine-77</td>
<td>Iodine-123</td>
<td>Xenon-122</td>
</tr>
<tr>
<td>Cadmium-109</td>
<td>Iodine-124</td>
<td>Xenon-127</td>
</tr>
<tr>
<td>Carbon-11</td>
<td>Iron-52</td>
<td>Yttrium-86</td>
</tr>
<tr>
<td>Chlorine-34m</td>
<td>Iron-55</td>
<td>Yttrium-88</td>
</tr>
<tr>
<td>Cobalt-55</td>
<td>Krypton-81m</td>
<td>Zinc-62</td>
</tr>
<tr>
<td>Cobalt-57</td>
<td>Lead-201</td>
<td>Zinc-63</td>
</tr>
<tr>
<td>Copper-61</td>
<td>Lead-203</td>
<td>Zirconium-89</td>
</tr>
<tr>
<td>Copper-64</td>
<td>Mercury-195m</td>
<td></td>
</tr>
<tr>
<td>Copper-67</td>
<td>Nitrogen-13</td>
<td></td>
</tr>
</tbody>
</table>
2. Industrial accelerators
Ion implantation

- Electrostatic accelerators are used to deposit ions in semiconductors.
Electron beam processing

In the US, potential markets for industrial electron beams total $50 billion per year.

33% Wire cable tubing
32% Ink curing
17% shrink film
7% service
5% tires
6% other

When polymers are cross-linked, can become:
- stable against heat,
- increased tensile strength, resistance to cracking
- heat shrinking properties etc

http://rsccnuclearcable.com/capabilities.htm
Manufacturers of medical disposables have to kill every germ on syringes, bandages, surgical tools and other gear, without altering the material itself.

E-beam sterilisation works best on simple, low density products.

Advantages: takes only a few seconds (gamma irradiation can take hours)

Disadvantages: limited penetration depth, works best on simple, low density products (syringes)

The IBA rhodotron – a commercial accelerator used for e-beam sterilisation
Food irradiation

‘Cold pasteurisation’ or ‘electronic pasteurisation’
Uses electrons (from an accelerator) or X-rays produced using an accelerator.

The words ‘irradiated’ or ‘treated with ionising radiation’ must appear on the label packaging.

In the US all irradiated foods have this symbol.

Foods authorised for irradiation in the EU:

- Lower dose
- Higher dose
Other uses in industry...

- Hardening surfaces of artificial joints
- Removal of $\text{NO}_x$ and $\text{SO}_x$ from flue gas emissions
- Scratch resistant furniture

Treating waste water or sewage
Purifying drinking water
(Without additional chemicals...)

Irradiating topaz and other gems with electron beams to change the colour

3. Synchrotron Light Sources

Image courtesy of ESRF
Synchrotron radiation is emitted by charged particles when accelerated radially.

Produced in synchrotron radiation sources using bending magnets, undulators and wigglers.
Synchrotron radiation: microwaves to hard x-rays (user can select)
High flux = quick experiments!
Pulsed structure = resolution of processes down to picoseconds
X-Ray crystallography

2014 was the International Year of Crystallography

Protein crystallography is a standard technique at synchrotron light sources (Diamond light source has 5 beamlines devoted to it)

The hardest part is forming the crystal...

For some great overview videos of crystallography, see: http://www.richannel.org/collections/2013/crystallography
Diffraction pattern from pea lectin
Biology

Reconstruction of the 3D structure of a nucleosome (DNA packaging) with a resolution of 0.2 nm

Archeology/Heritage

A synchrotron X-ray beam at the SSRL facility illuminated an obscured work erased, written over and even painted over of the ancient mathematical genius Archimedes, born 287 B.C. in Sicily.

Using X-Ray induced fluorescence

In 1990 scientists determined the structure of a strain of foot & mouth virus using Daresbury SRS.
4. Neutron Spallation Sources
'Neutrons tell you where atoms *are* and what atoms *do*'

https://youtu.be/VESMU7JfVHU?t=21
ISIS Accelerators and Targets

- H⁻ ion source (17 kV)
- 665 kV H⁻ RFQ
- 70 MeV H⁻ linac
- 800 MeV proton synchrotron
- Extracted proton beam lines
- Targets
- Moderators

Pulsed beam of 800 MeV (84% speed of light) protons at 50 Hz
Average beam current is 230 µA (2.9×10¹³ ppp)

184 kW on target (148 kW to TS-1 at 40 pps, 36 kW to TS-2 at 10 pps).

\[ P = 800[ MV ] \times 230[ \mu A ] = 184[ kW ] \]
Calculating beam power

- Power = Work/time
  \[ P = \frac{W}{T} \]

- Work = force x distance
  \[ W = Fd \]

- Force on particle in an electric field
  \[ F = qE \]

- We know the electric field is (voltage/distance) and the protons (charge +1) have gained 800 MeV, so V=800MV.

- Also know current = charge/time
  \[ P = 800\,[MV] \times 230\,[\mu A] = 184\,[kW] \]
Image courtesy ISIS, STFC.
Unblocking oil pipes

• Asphaltenes are a complex mixture of molecules that can sometimes block oil pipes.
• Research to more easily predict and prepare for the formation of asphaltene deposits.
• Result in fewer blockages and big savings for the oil industry.

“ISIS allowed us to understand more clearly how asphaltenes aggregate, an important observation from a flow assurance point of view and should allow more efficient extraction of hydrocarbons in the future.”

– Edo Boek, Schlumberger Cambridge Research, Senior Research Scientist
Stresses in Airbus A380 Wing

• Aircraft manufacturer Airbus has used ISIS since 2006
• Research into aluminium alloy weld integrity for aircraft programmes
• Residual stresses from welding cause weaknesses and the possibility of cracks
• ISIS neutrons look deep inside engineering components to measure stress fields

“Residual stress measurement at ISIS has been invaluable in researching and developing existing and novel material manufacturing and processing techniques.”

– Richard Burguete, Airbus Experimental Mechanics Specialist
Understanding infant lung structure

• Natural lung surfactant allows oxygen into the bloodstream.
• Absence in premature babies causes breathing difficulties.
• ISIS mimicked change in lung capacity to discover how proteins and phospholipids act together.
• Helping to develop synthetic lung surfactants which can be more precisely targeted at clinical needs to help save babies’ lives.

“ISIS is the premier place in the world to work with neutrons and liquid surfaces. In collaboration with the University of Queensland we were able to discover how proteins and phospholipids act together to enable lung function.”

- Dr Stephen Holt, ISIS neutron scientist
Fast neutron testing for the semiconductor industry

• Atmospheric neutrons collide with microchips and upset microelectronic devices every few seconds

• 300 x greater effect at high altitude

• ISIS enables manufacturers to mitigate against the problem of cosmic radiation

• Increased confidence in the quality and safety of aerospace electronic systems

“ISIS is one of few facilities in the world capable of producing enough very high energy neutrons to perform accelerated testing.”

– Andrew Chugg, MBDA, SEEDER consortium
5. Energy and Security Applications
Cargo scanning

Cargo containers scanned at ports and border crossings

Accelerator-based sources of X-Rays can be far more penetrating (6MV) than Co-60 sources.

Container must be scanned in 30 seconds.

Image source: Varian medical systems

Image: dutch.euro
Materials testing for fusion

Source: IFMIF.org
“deuterium-tritium nuclear fusion reactions will generate neutron fluxes in the order of $10^{18} \text{ m}^{-2}\text{s}^{-1}$ with an energy of 14.1 MeV that will collide with the first wall of the reactor vessel”

International Fusion Material Irradiation Facility (IFMIF)

40 MeV
2 x 125mA linacs
CW deuterons, 5MW each
Beams will overlap onto a liquid Li jet
To create conditions similar to in a fusion reactor

To de-risk IFMIF, first a test accelerator ‘LIPAc’ is being built

Installation of ‘LIPAc’ test accelerator has started in Japan
Accelerator Driven Systems

Transmutation of nuclear waste isotopes or energy generation

Major challenges for accelerator technology in terms of beam power (>10MW) and reliability
6. Historical and cultural applications
Radiocarbon Dating

For more accuracy, isolate C-14 from other isotopes
“AMS” = Accelerator Mass Spectrometry
Accelerators can study art

This painting “Patch of grass” by Vincent van Gogh was the first one analysed by a particle accelerator

Used X-ray fluorescence technique Distribution of Hg and Sb pigment allowed a reconstruction of underlying image

It showed a portrait of a woman underneath

Accelerators can help spot art forgeries

Ion Beam Analysis shows us the chemical composition of pigments used in paint

This allows art historians to compare them with paints available to artists like Leonardo da Vinci
Accelerators in archaeology

The interior of samples can be studied using accelerators without destroying them.

Pottery from Armenia, dating back to 1300 BC, is set up for a synchrotron experiment.

Image: Argonne National Laboratory
Accelerators can make food taste better

Of the six possible crystal forms, the fifth (form V) produces the best quality chocolate

Cadbury used X-rays from a particle accelerator to study how cocoa crystallises
Finally, just one more application...

Detecting wine fraud

Use ion beam to test the bottle of “antique” wine – chemical composition of the bottle compared to a real one.

“In a recent and spectacular case, American collector William Koch sued a German wine dealer, claiming four bottles – allegedly belonging to former U.S. president Thomas Jefferson – purchased for 500,000 dollars, were fake. The case has yet to be settled.”

- http://www.cosmosmagazine.com
Next time someone asks you what accelerators are for...

“A beam of the right particles with the right energy at the right intensity can shrink a tumor, produce cleaner energy, spot suspicious cargo, make a better radial tire, clean up dirty drinking water, map a protein, study a nuclear explosion, design a new drug, make a heat-resistant automotive cable, diagnose a disease, reduce nuclear waste, detect an art forgery, implant ions in a semiconductor, prospect for oil, date an archaeological find, package a Thanksgiving turkey or...

...discover the secrets of the universe.”

-Accelerators for Americas Future Report, pp. 4, DoE, USA, 2011
Accelerators in the world >24000

Source (2007):
http://www.worldscientific.com/worldscibooks/10.1142/6272

Engines of Discovery. A Century of Particle Accelerators. Andrew Sessler, Edmund Wilson