Applications of Accelerators

CERN Introductory Accelerator School
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“A beam of particles is a very useful tool...”

Outline

1. Medical imaging and treatment
2. Industrial uses of accelerators
3. Synchrotron light sources
4. Neutron sources
5. Energy, environment & security applications
6. Historical & cultural applications
1. Medical Applications
Change in three measures of cancer mortality, United Kingdom, 1990 to 2017

This chart compares cancer deaths, the cancer death rate, and the age-standardized death rate.

Source: Global Burden of Disease [IHME]
Every sixth death in the world

But diagnosis is no longer a death sentence!

Source: IHME, Global Burden of Disease (GBD)
Note: All cancer types with less than 100,000 global deaths in 2016 into a collective category 'Other cancers'.
**X-ray Radiotherapy (XRT)**

Around **half of all cancer patients** in HICs benefit from RT

- Linac (S-band)
- Achromatic Bend
- Foil to produce x-rays
- Collimation system

Image: copyright Varian medical systems
A Global Challenge in Healthcare:

- By 2035, 75% of cancer deaths worldwide will be in LMICs
- Severe shortfall of LINACs & issues with machine failures

STELLA Collaboration Formed to Address this Issue
Charged Particle Therapy

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

Bragg Peak
Energy loss in matter (+tissue)

\[-\left\langle \frac{dE}{dx} \right\rangle = \frac{4\pi}{m_e c^2} \cdot \frac{n z^2}{\beta^2} \left( \frac{e^2}{4\pi\varepsilon_0} \right)^2 \cdot \left[ \ln \left( \frac{2m_e c^2 \beta^2}{I \cdot (1 - \beta^2)} \right) - \beta^2 \right]\]

\[
\beta = \frac{v}{c}
\]

\[
v \quad \text{velocity of the particle}
\]

\[
E \quad \text{energy of the particle}
\]

\[
x \quad \text{distance travelled by the particle}
\]

\[
c \quad \text{speed of light}
\]

\[
z \quad \text{charge of the particle}
\]

\[
e \quad \text{charge of the electron}
\]

\[
m_e \quad \text{rest mass of the electron}
\]

\[
n \quad \text{electron density of the target}
\]

\[
I \quad \text{mean excitation potential of the target}
\]

\[
\varepsilon_0 \quad \text{vacuum permittivity}
\]

High speed -> small energy loss
Low speed -> high energy loss
Particle therapy facilities in operation

https://www.thegreenjournal.com/article/S0167-8140(18)30146-4/fulltext
Proton & Ion 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
Challenges in Particle Therapy:

EFFICACY/QUALITY  COST/SIZE/EFFICIENCY

MedAustron: a facility which emerged from CERN study ‘PIMMS’. A new study ‘NIMMS’ is underway.
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, 3He, 4He beams

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

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2. Industrial accelerators
Ion implantation

• Electrostatic accelerators are used to deposit ions in semiconductors.

Images courtesy of Intel
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](http://rsccnuclearcable.com/capabilities.htm)
Equipment sterilisation

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
Gemstone Irradiation


‘Irradation and Radioactivity’, Gems and Gemology, 1988
Other industrial uses

- Non-destructive testing (weld integrity etc)
- Hardening surfaces of artificial joints
- Scratch resistant furniture
- Hardening of tarmac


Image: https://www.mistrasgroup.com
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.
X-Ray 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
In 1990 scientists determined the structure of a strain of foot & mouth virus using Daresbury SRS.

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

The main SARS-COV-2 protease from D. Owen, Diamond Light Source, UK

More info: https://cerncourier.com/a/synchrotrons-on-the-coronavirus-frontline/
Archaeology/Heritage

Using X-Ray induced fluorescence

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.

Pottery from Armenia, dating back to 1300 BC, is set up for a synchrotron experiment: accelerators have the advantage of being non-destructive.
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.
- High flux = fast experiments
- High brilliance – small divergence & partially coherent
- High stability - submicron
- Polarisation
- Pulsed

Synchrotron radiation: microwaves to hard x-rays (user can select)
Diffraction pattern from pea lectin
4. Neutron Spallation Sources
‘Neutrons tell you where atoms are and what atoms do’
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 × 10\(^{13}\) ppp)

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

\[ P = 800 [MV] \times 230 [A] = 184 [kW] \]
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, Environment & 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
Wastewater Irradiation

Remove organic compounds and disinfect wastewater.

Can be used to treat/reclaim:
- Textile Dyeing
- Pharmaceutical
- Petrochemical
- Municipal Wastewater
- Contaminated Underground Water

1 MeV, High Current, scanning system

Also used for removal of NO$_x$ and SO$_x$ from flue gas emissions

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
IBA techniques: help spot art forgeries

- Ion Beam Analysis (MeV) shows us the chemical composition of pigments used in paint
- Backscattered radiation can give detailed analysis of atoms present in surface.
- This allows art historians to compare them with paints available to artists like Leonardo da Vinci
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 (red) and Sb (yellow) pigment allowed a reconstruction of underlying image.

It showed a portrait of a woman underneath.

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
“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