Applications of Accelerators

CERN Introductory Accelerator School
Santa Susana, Spain, 2024

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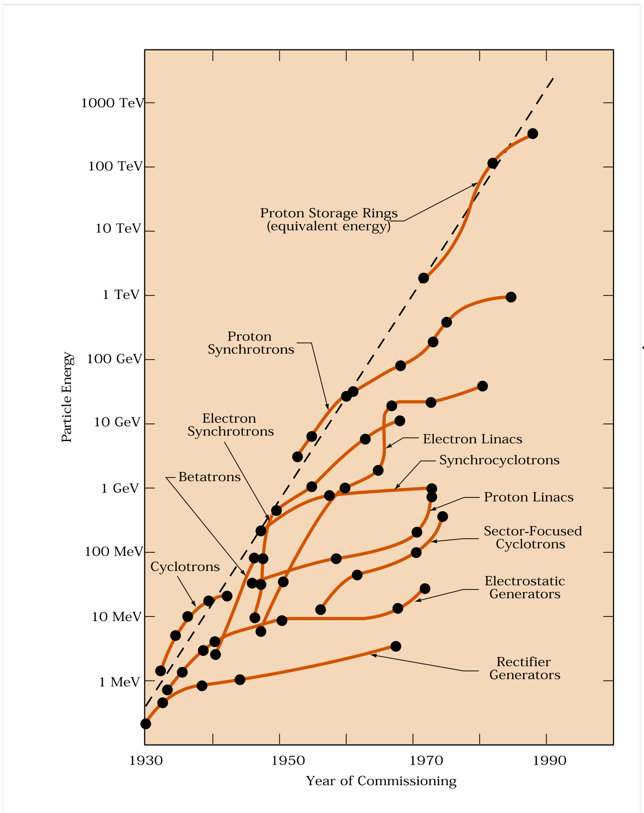
The CERN Accelerator School

Copyright statement and speaker's release for video publishing

Where do breakthrough technologies come from?

Many innovations emerge from interplay between curiosity driven research and societal need



https://www.symmetrymagazine.org/article/october-2009/deconstruction-livingston-plot

particle physics

vaccines, archaeology, etc…

proton therapy

radiotherapy, security

water, food, materials treatment, sterilisation

John Womersley, former CEO of STFC (UK) said:

"Particle physics is unreasonable. It makes unreasonable demands on technology. And when those technologies, those inventions, those innovations happen, they spread out into the economy, and they generate a huge impact."

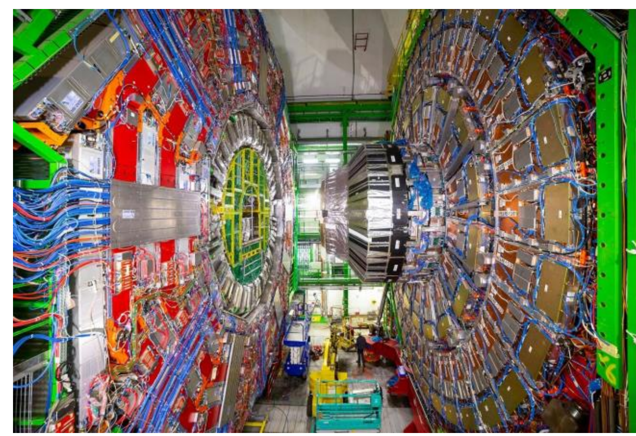
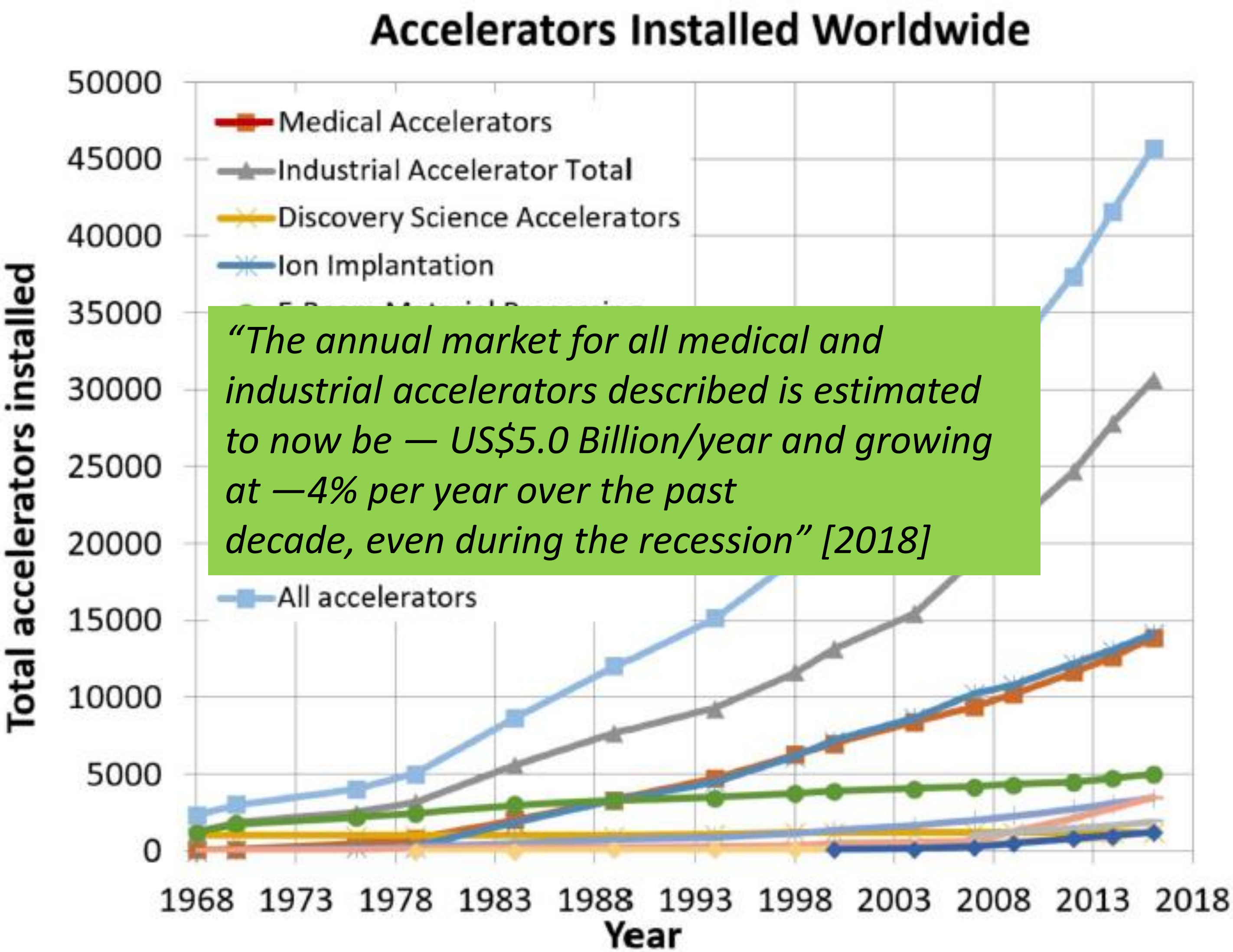
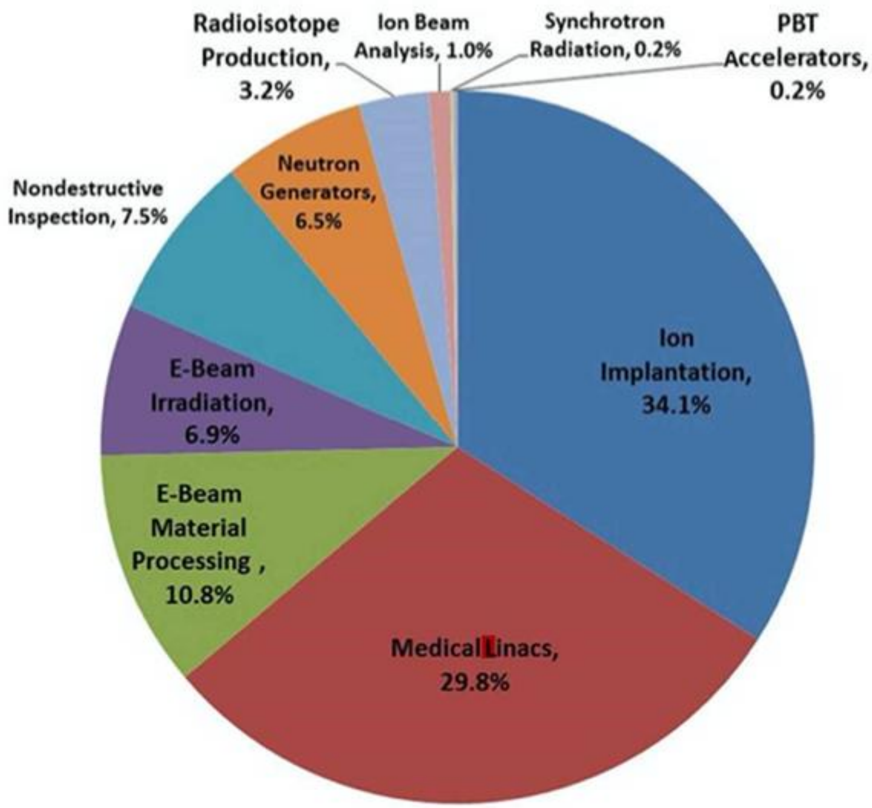


Image: CMS, CERN



Doyle, McDaniel, Hamm, *The Future of Industrial Accelerators and Applications, SAND2018-5903B*

“A beam of particles is a very useful tool...”



Doyle, McDaniel, Hamm, *The Future of Industrial Accelerators and Applications, SAND2018-5903B*

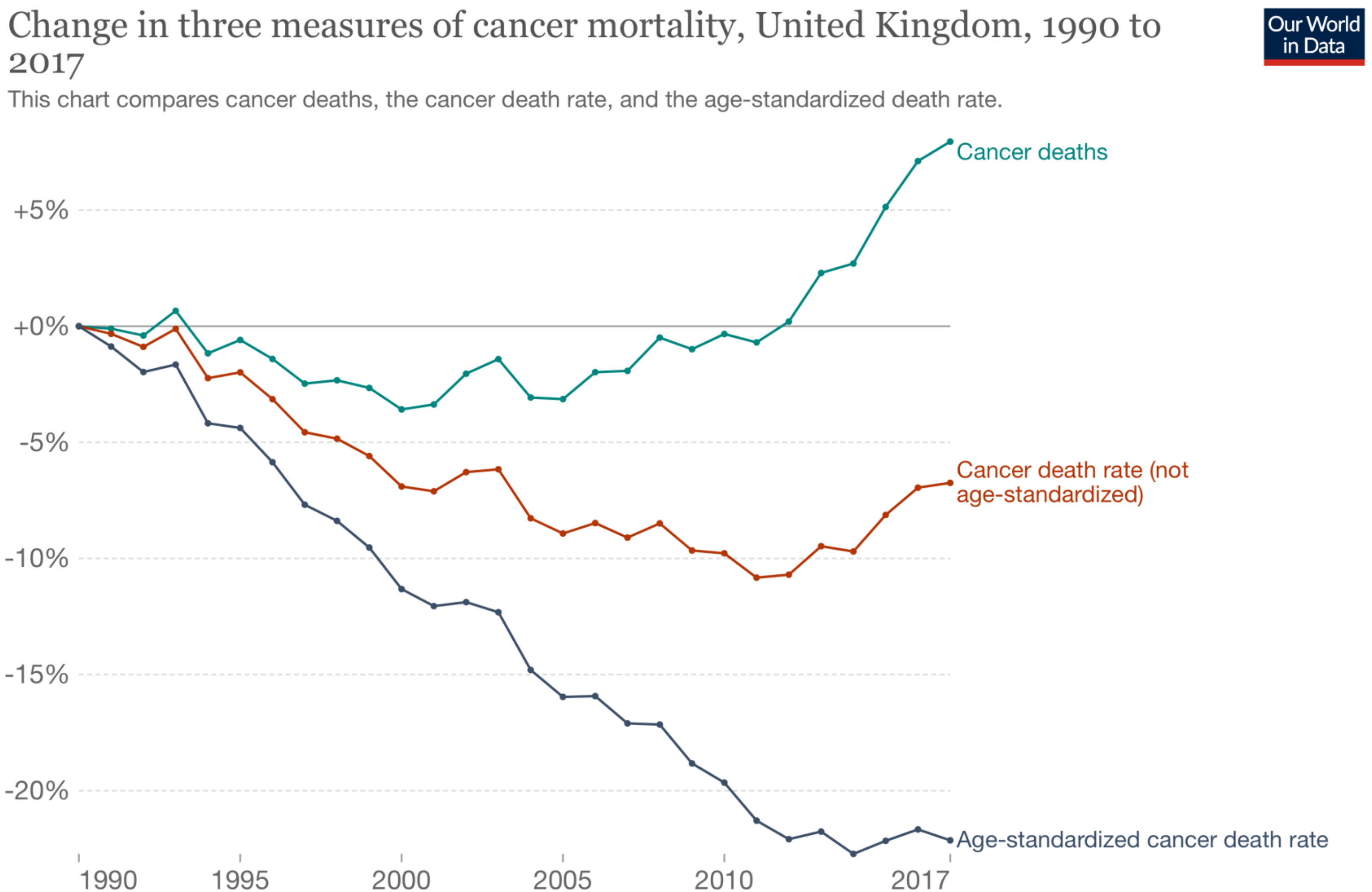
Outline

1. Medical imaging and treatment
2. Industrial uses of accelerators
3. Sustainability & security applications
4. Historical & cultural applications
5. Large facilities: synchrotron light sources / neutron sources
6. Challenges for the future

1. Medical Applications

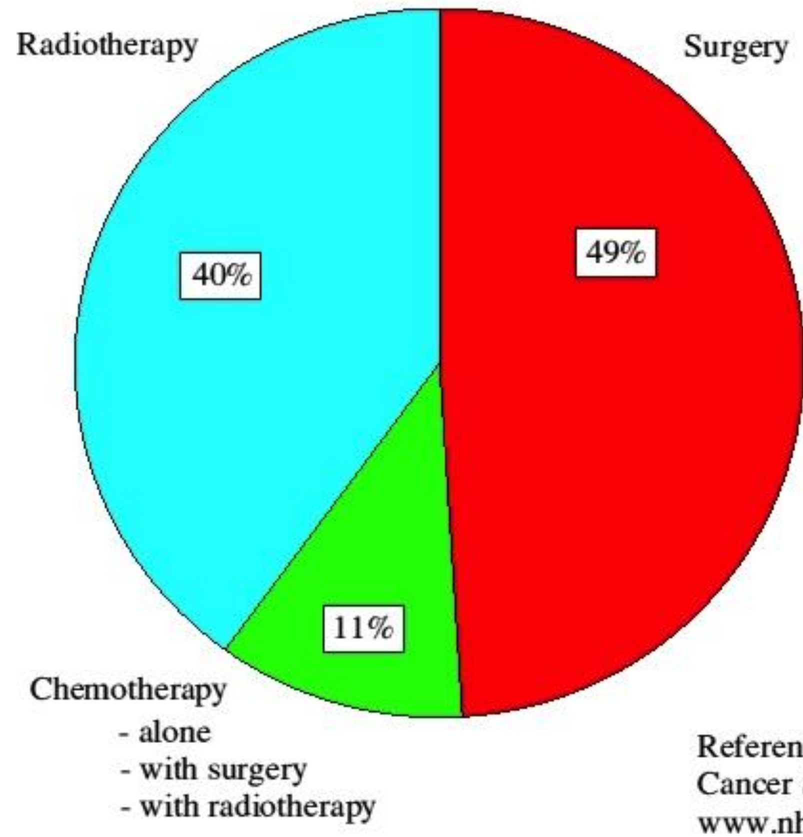
Change in three measures of cancer mortality, United Kingdom, 1990 to 2017

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



Source: Global Burden of Disease [IHME]

Patients cured by the major cancer treatment modalities



Reference
Cancer Services Collaborative 2002
www.nhs.uk/npat

X-ray Radiotherapy (RT)

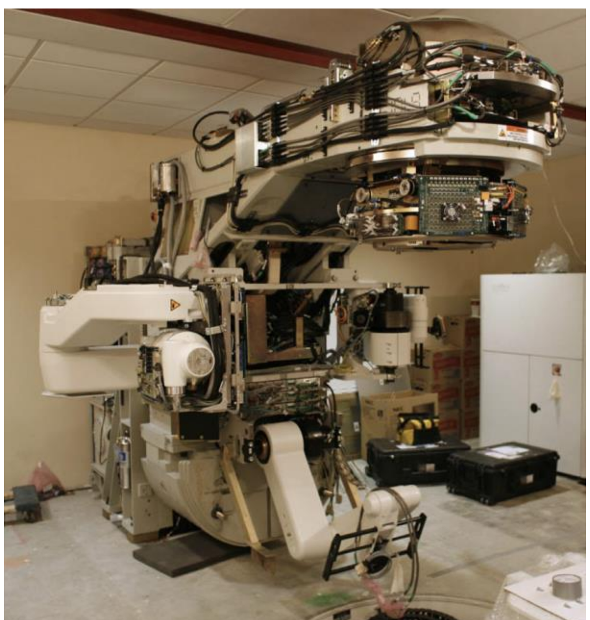
Around **half of all cancer patients** in HICs benefit from RT

Linac (S-band)

Achromatic Bend

Foil to produce x-rays

Collimation system



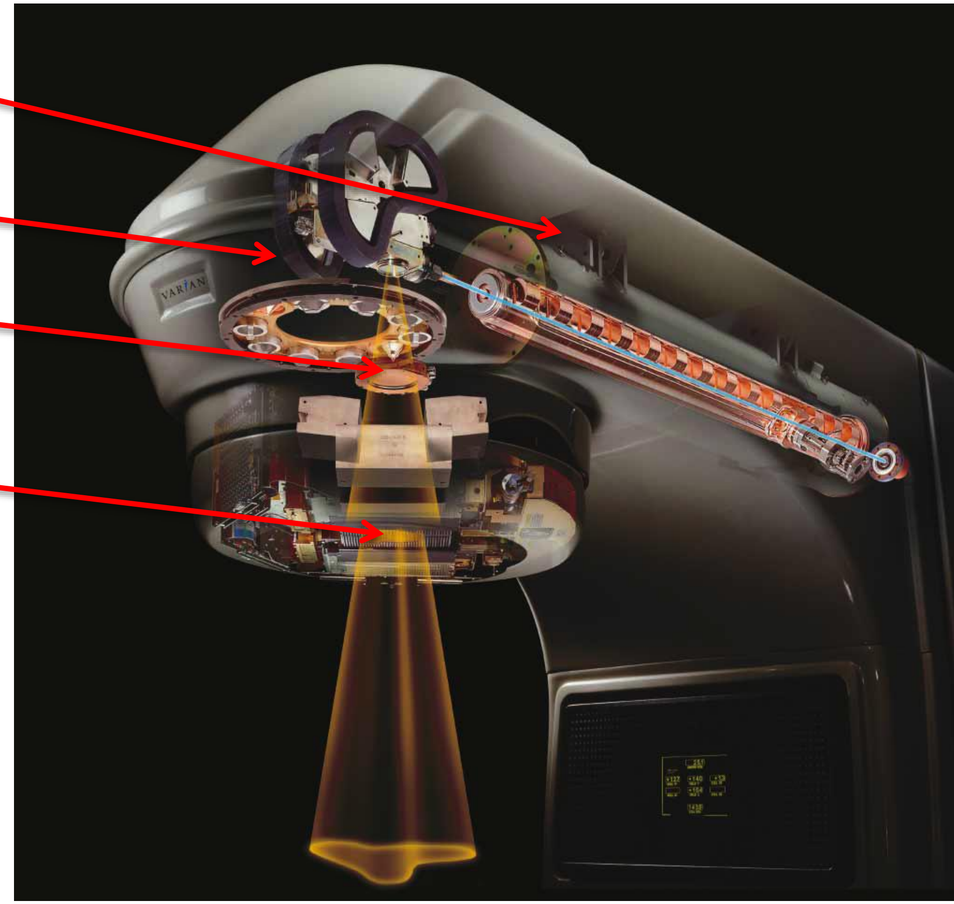
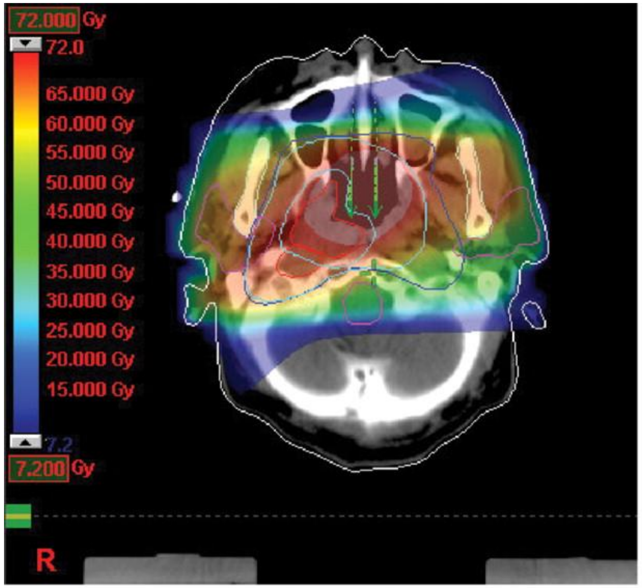


Image: copyright Varian medical systems


72.000 Gy
72.0
65.000 Gy
60.000 Gy
55.000 Gy
50.000 Gy
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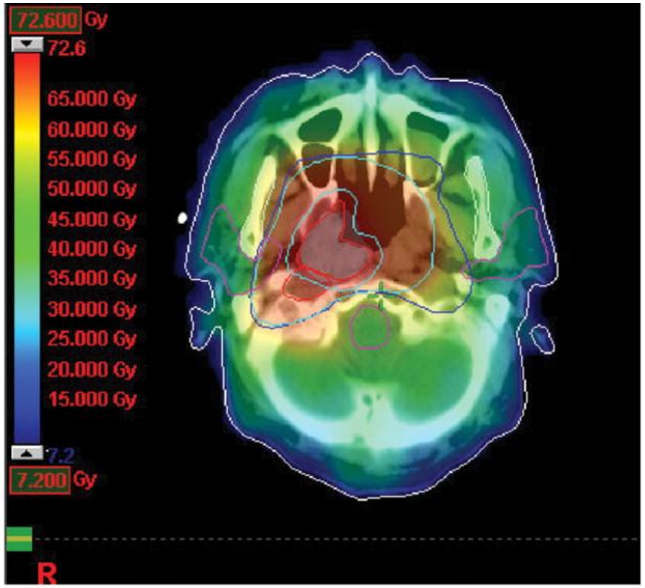
25.000 Gy
20.000 Gy
15.000 Gy
7.2
7.200 Gy
R

(a)


72.600 Gy
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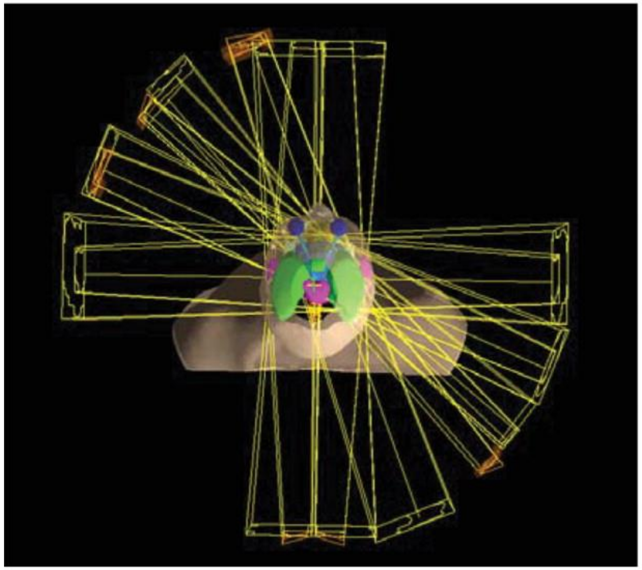
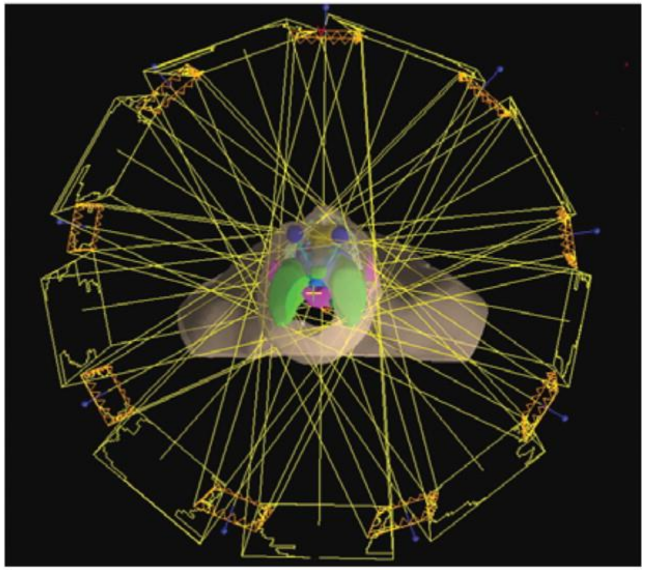
30.000 Gy
25.000 Gy
20.000 Gy
15.000 Gy
7.2
7.200 Gy
R

(b)

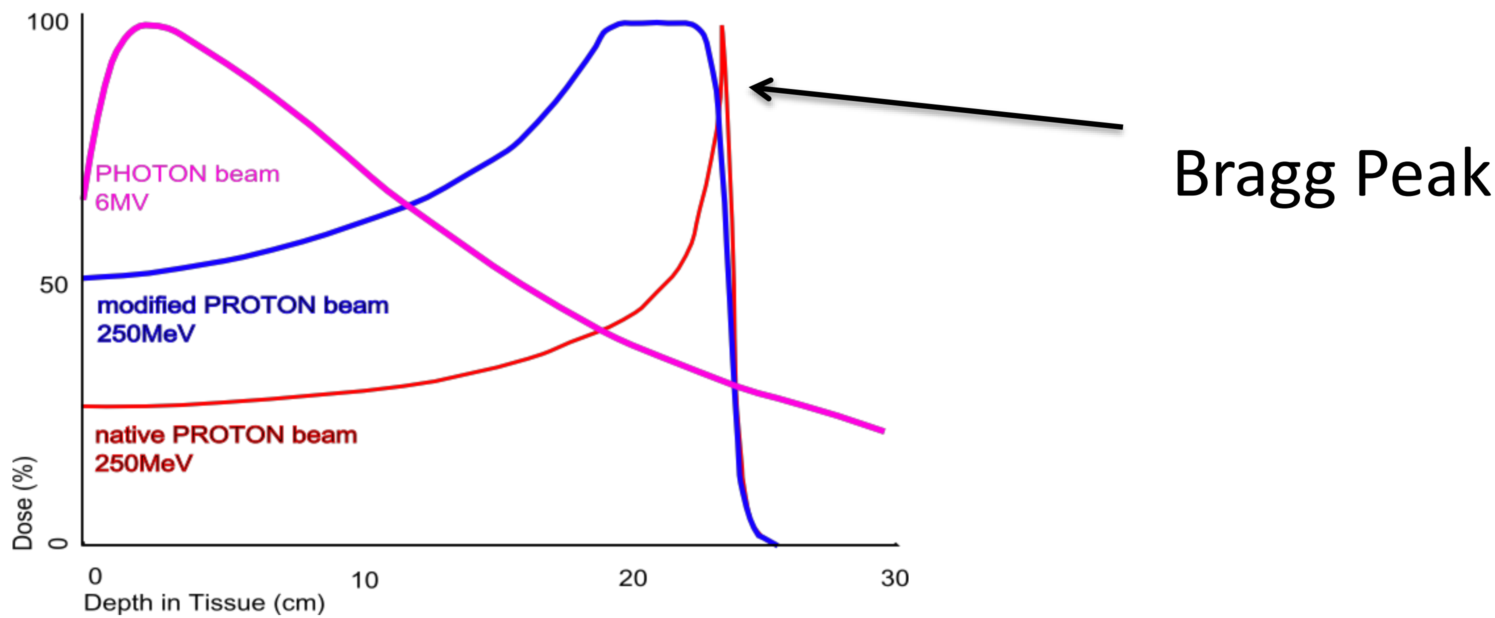


(c)



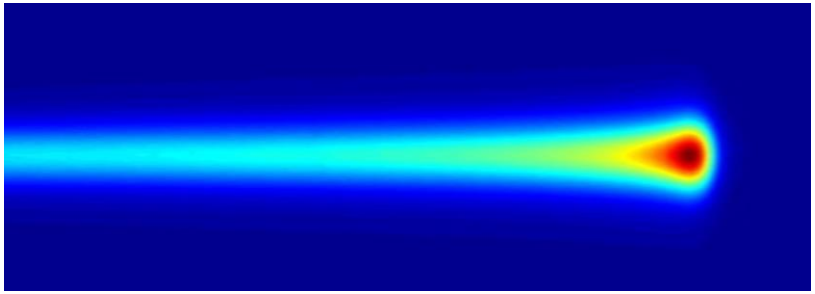
(d)

Charged Particle Therapy



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

Energy loss in matter (+tissue)



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

β $= v / c$

v velocity of the particle

E energy of the particle

x distance travelled by the particle

c speed of light

$z\,e$ particle charge

e charge of the electron

m_e rest mass of the electron

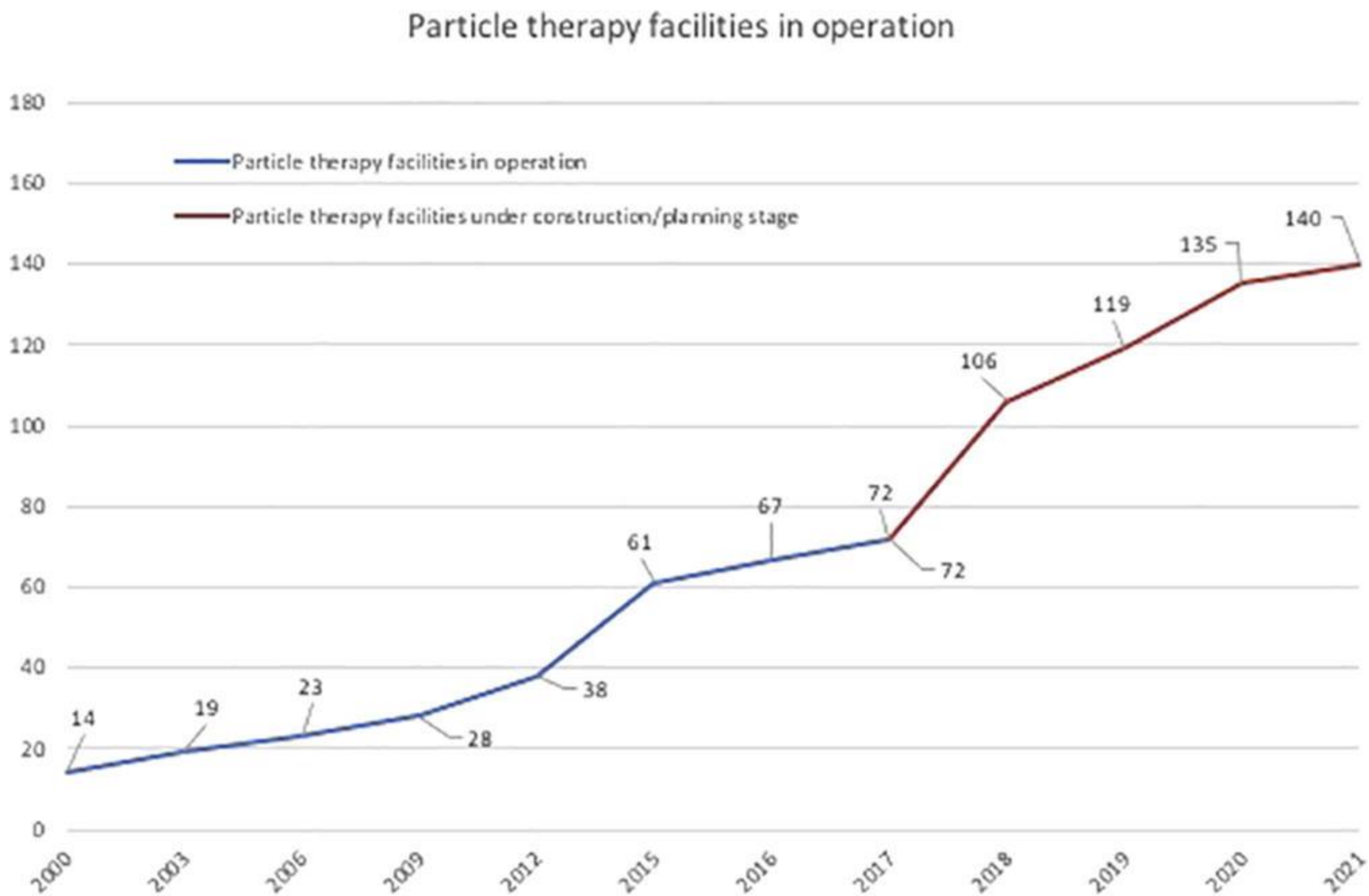
n electron density of the target

I mean excitation potential of the target

ε_0 vacuum permittivity

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

“More than 360'000 patients have been treated worldwide with particle therapy per end of 2022” – PTCOG 2022

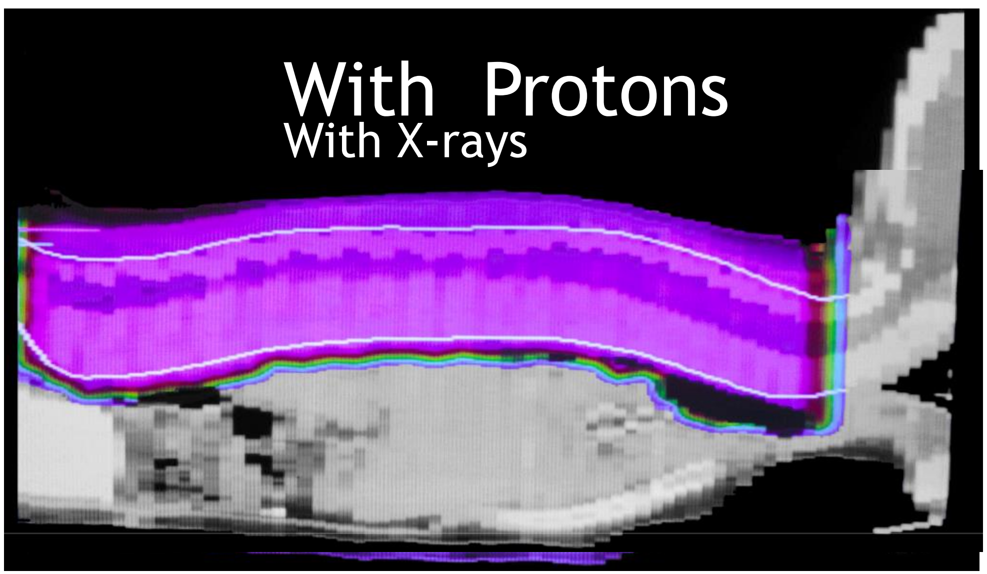


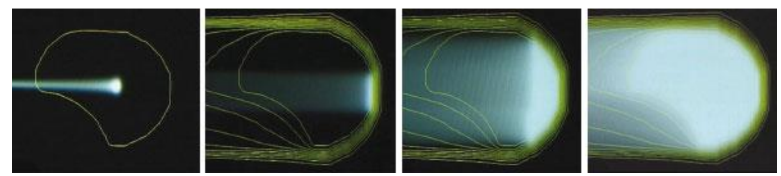
https://www.thegreenjournal.com/article/S0167-8140(18)30146-4/fulltext

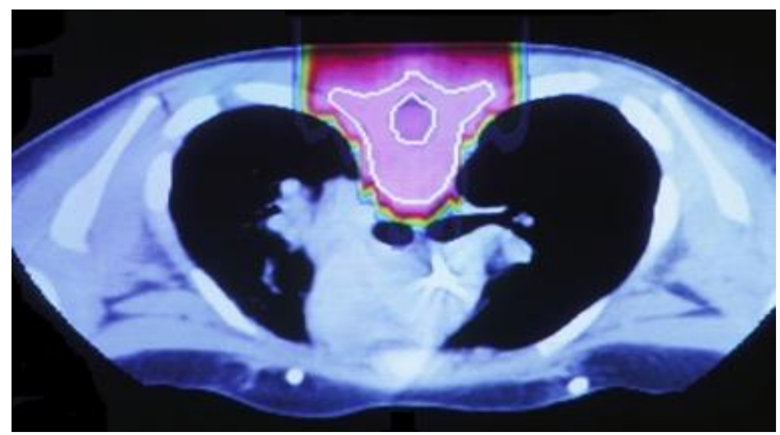
Proton & Ion therapy

- "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



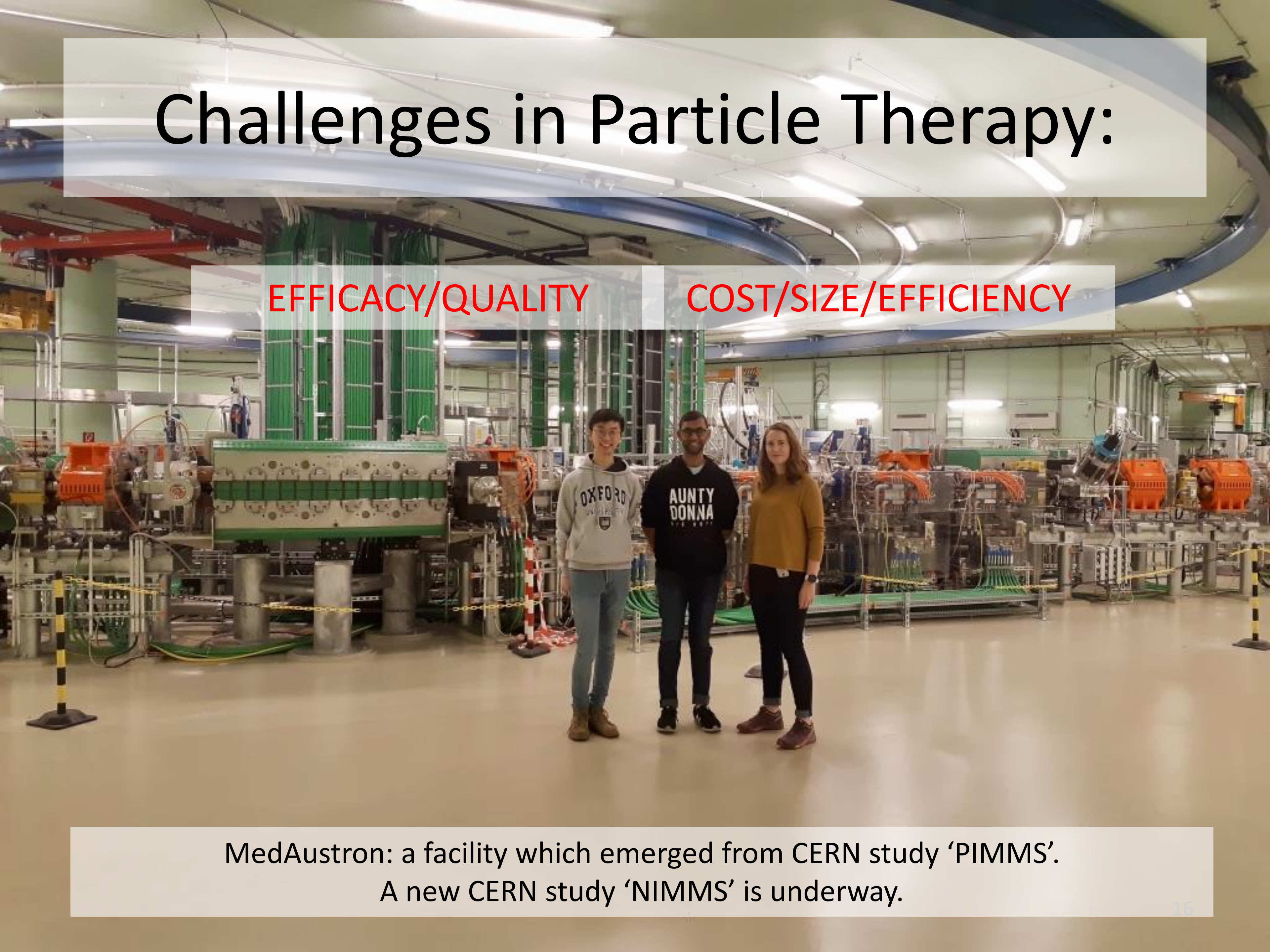




Challenges in Particle Therapy:

EFFICACY/QUALITY

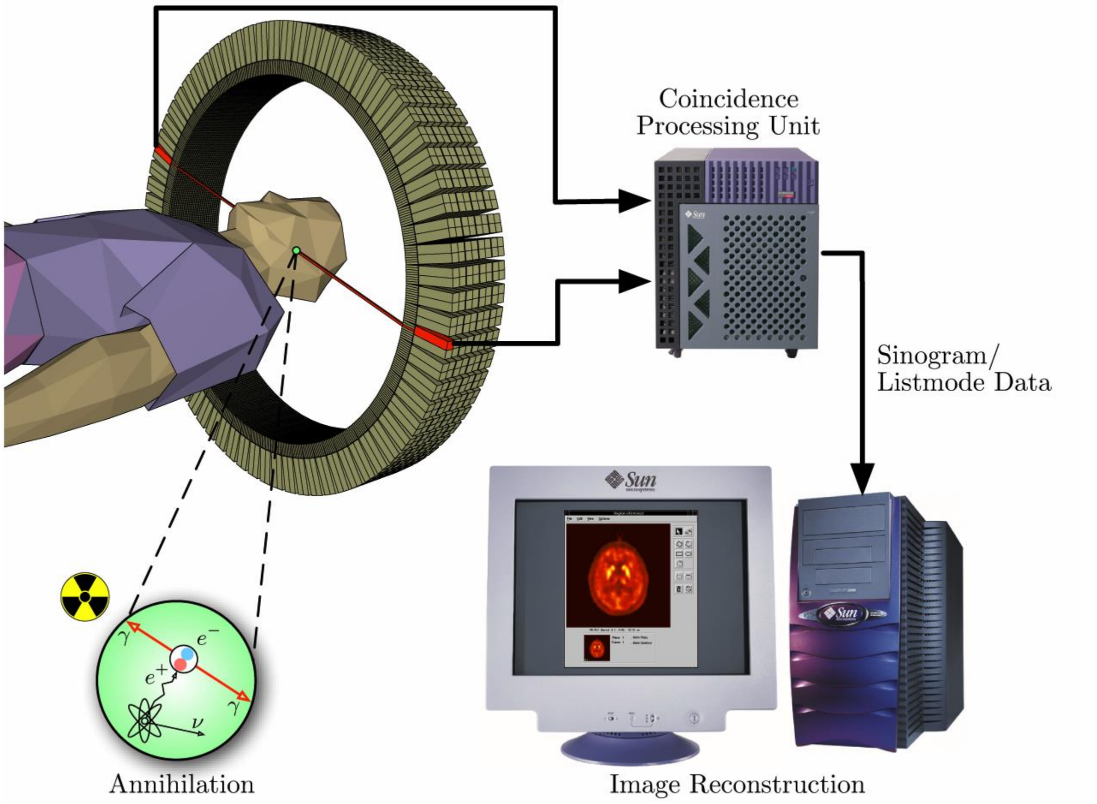
COST/SIZE/EFFICIENCY



MedAustron: a facility which emerged from CERN study ‘PIMMS’.
A new CERN 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

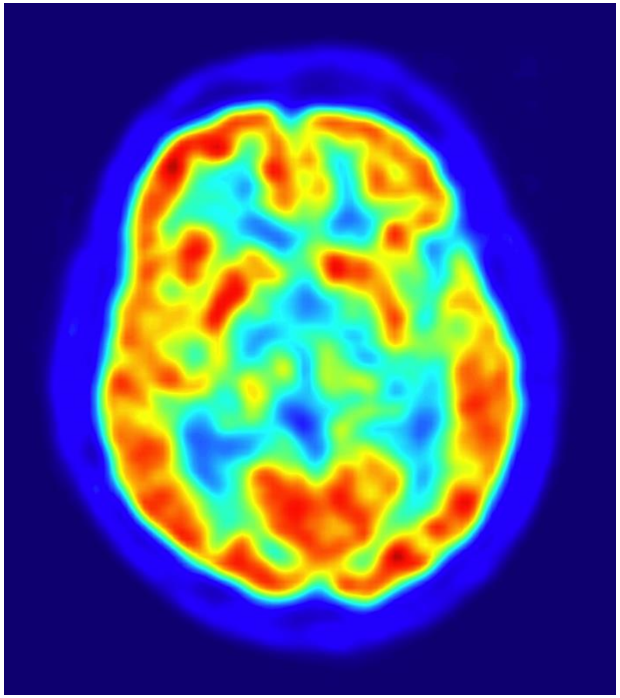
Radiopharmaceuticals

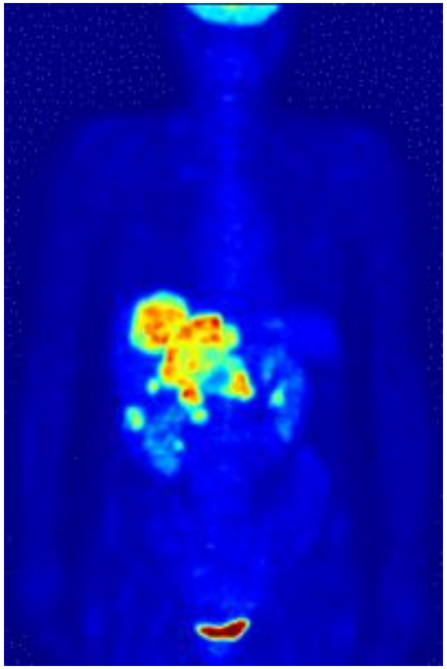
p, d, 3He, 4He
beams

Isotopes used for PET, SPECT and Brachytherapy etc…

TABLE 2.1. THE RADIOISOTOPES THAT HAVE BEEN USED AS TRACERS IN THE PHYSICAL AND BIOLOGICAL SCIENCES

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

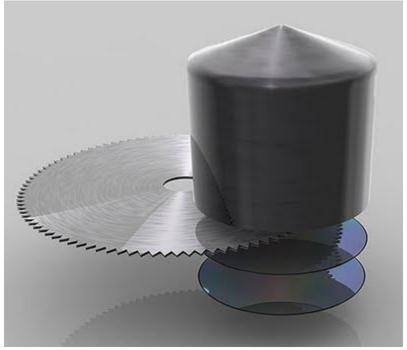
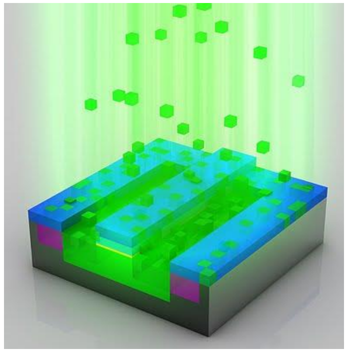
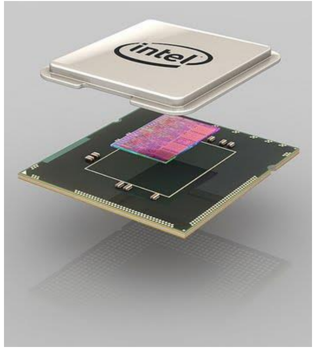




- Fluorodeoxyglucose or FDG carries the F18 to areas of high metabolic activity
- 90% of PET scans are in clinical oncology

2. Industrial accelerators

Ion implantation

Images courtesy of Intel

- Accelerators keV->MeV are used to deposit ions in semiconductors.

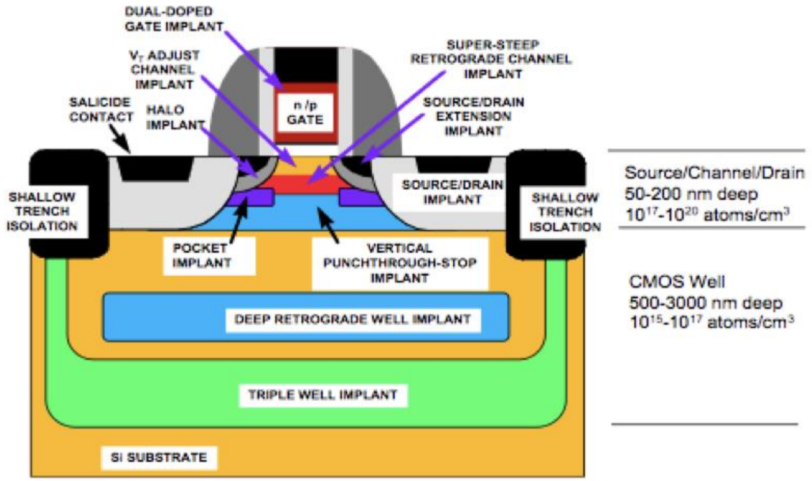


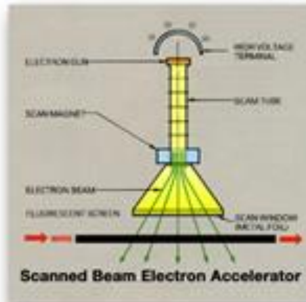
Figure 2: Sketch of major doped regions for a planar CMOS transistor.

Image: https://accelconf.web.cern.ch/pac2013/papers/weyb2.pdf

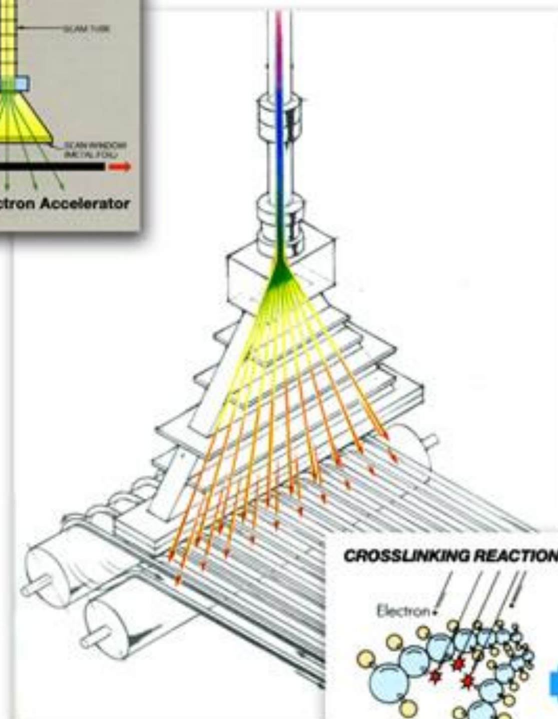
Electron beam processing

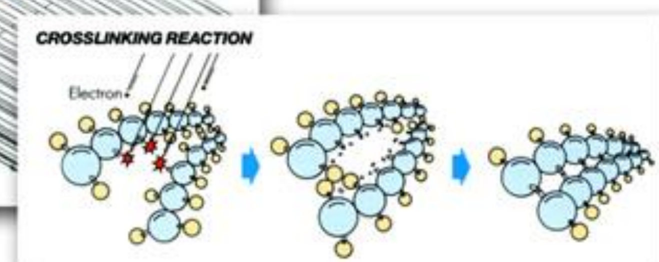
In the US, potential markets for industrial electron beams total $50 billion per year.

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



http://rsccnuclearcable.com/capabilities.htm





When polymers are cross-linked, can become:

- stable against heat,
- increased tensile strength, resistance to cracking
- heat shrinking properties etc

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.

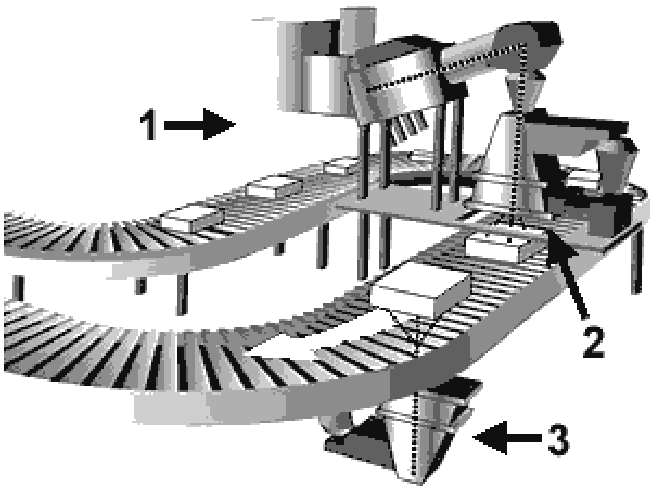
Advantages: takes only a few seconds (gamma irradiation can take hours)

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

40-50% of all disposable medical products manufactured in North America are currently radiation sterilized, primarily at 60Co irradiation facilities. – Hamm & Doyle, 2018

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.

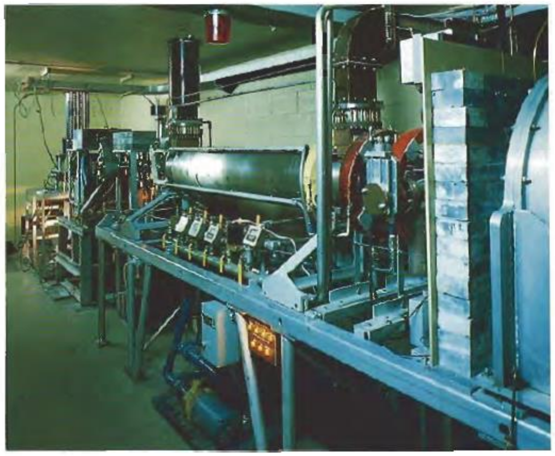
The words ‘irradiated’ or ‘treated with ionising radiation’ must appear on the label packaging.

In the US all irradiated foods have this symbol

Foods authorised for irradiation in the EU:

Lower dose → Higher dose

Gemstone Irradiation



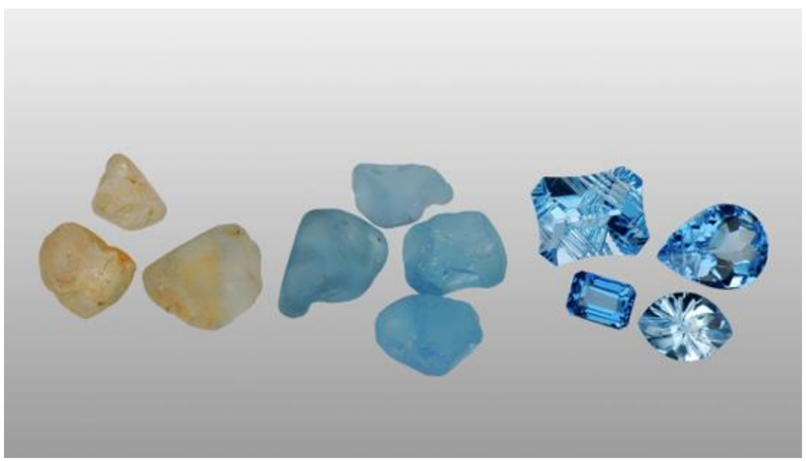


TABLE 2. Effects of irradiation treatment on various gem materials.[a]

Material	Starting color	Ending color
Beryl	Colorless	Yellow
	Blue	Green
Maxixe-type	Pale or colorless	Blue
Corundum	Colorless	Yellow
	Pink	Padparadscha
Diamond	Colorless or pale to yellow and brown	Green or blue (with heating, turns yellow, orange, brown, pink, red)
Fluorite	Colorless	Various colors
Pearl	Light colors	Gray, brown, "blue," "black"
Quartz	Colorless to yellow or pale green	Brown, amethyst, "smoky," rose
Scapolite[b]	Colorless, "straw," pink, or light blue	Blue, lavender, amethyst, red
Spodumene	Colorless to pink	Orange, yellow, green, pink[c]
Topaz	Yellow, orange	Intensify colors
	Colorless, pale blue	Brown, blue (may require heat to turn blue), green
Tourmaline	Colorless to pale colors	Yellow, brown, pink, red, bicolor green-red
	Blue	Purple
Zircon	Colorless	Brown to red

[a] *Adapted from Nassau (1984).*
[b] *Charles Key, pers. comm., 1988.*
[c] *George Drake, pers. comm., 1988.*

http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/irradiated-gemstones.html

http://www.symmetrymagazine.org/article/october-2009/cleaner-living-through-electrons

'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

http://www.accelerators-for-society.org/case-studies/case-study-car.php

Image: https://www.mistrasgroup.com

3. Sustainability & Security Applications

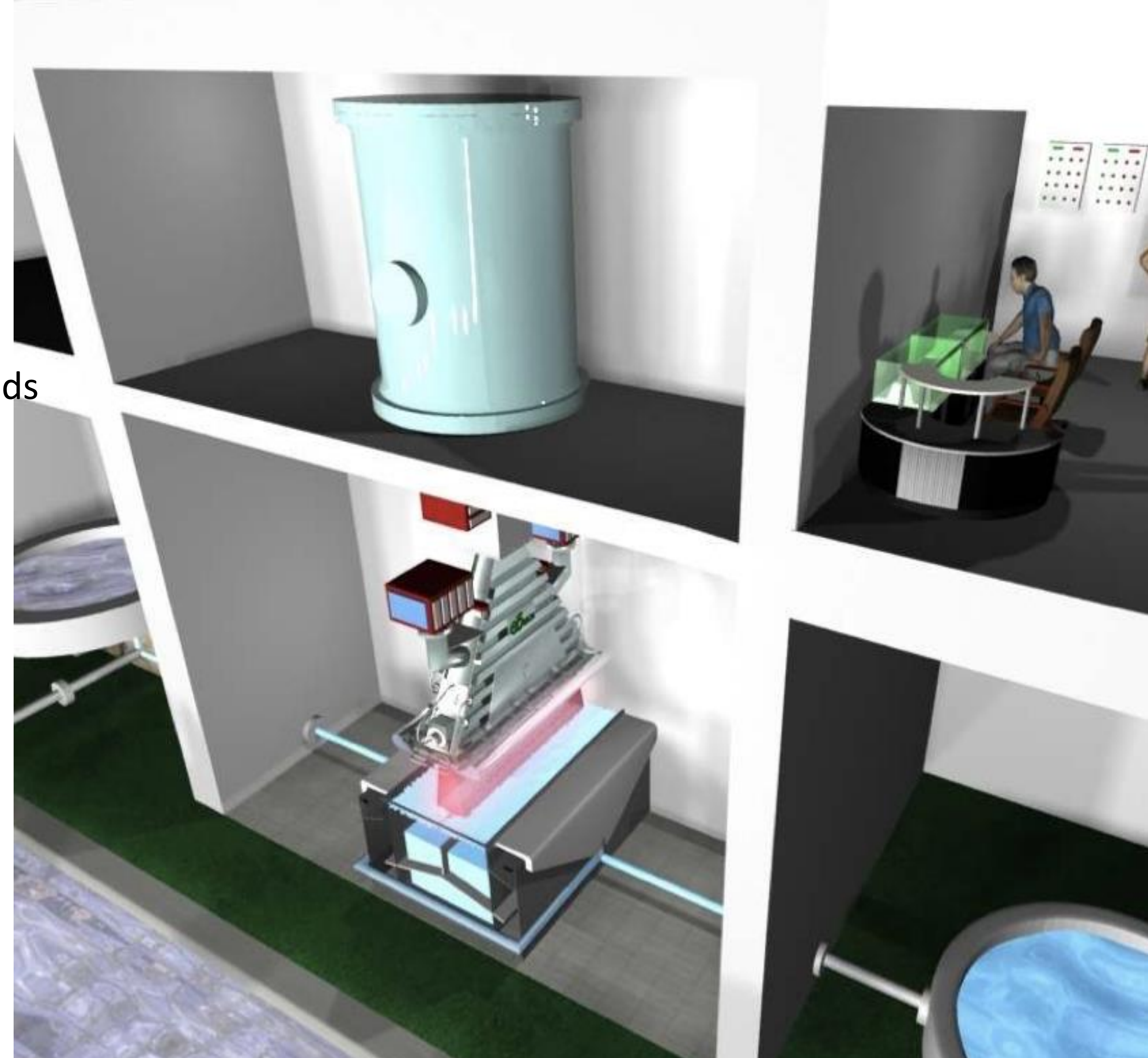
Wastewater Irradiation

Remove organic compounds and disinfect wastewater.

Can be used to treat/reclaim:

- Textile Dyeing
- Pharmaceutical
- Petrochemical
- Municipal Wastewater
- Contaminated Underground Water

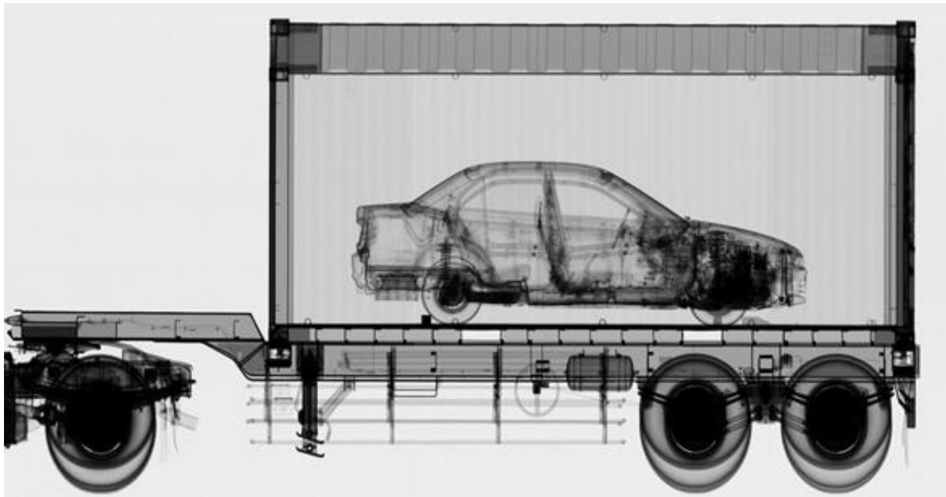
1 MeV, High Current, scanning system



Also used for removal of NO_x and SO_x from flue gas emissions

https://www-pub.iaea.org/MTCD/publications/PDF/P1433_CD/datasets/presentations/SM-EB-23.pdf

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

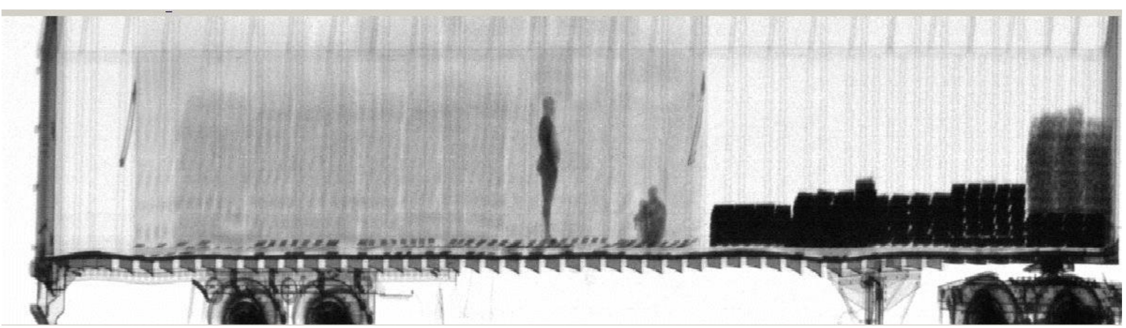


Image: dutch.euro

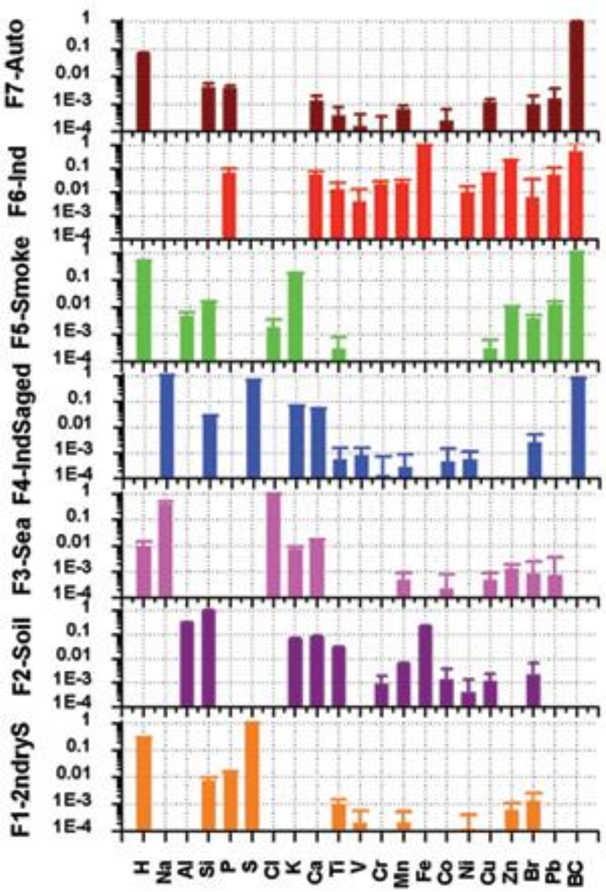
Ion beam analysis

Bombarding with ions excites materials, which give off characteristic bursts of x-rays, gammas etc = a ‘fingerprint’ for elemental analysis.

ANSTO Centre for Accelerator Science

Studying Aerosols and Pollutants

“Using ion beam analysis methods, it is possible to not only determine the number of minute quantities of pollutants in the air but also to identify their sources,” - David Cohen, ANSTO

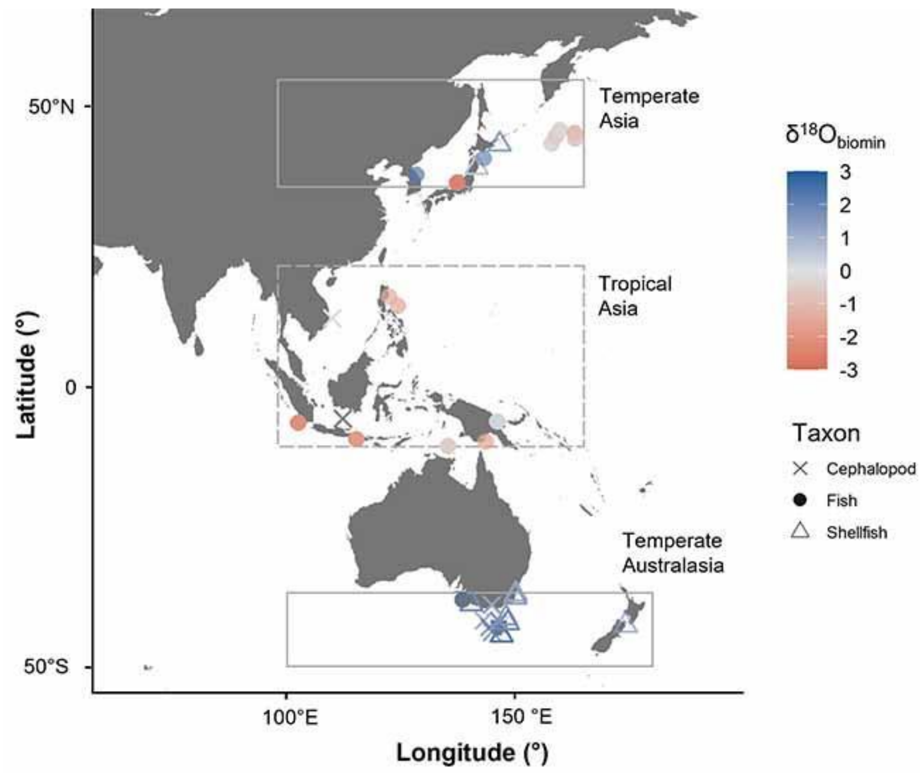


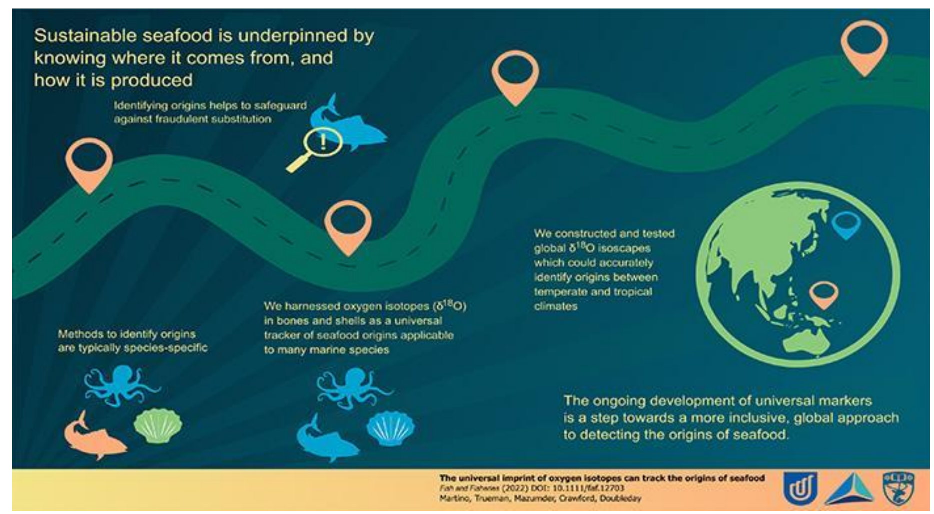
“up to half of the total sulfate air pollution in the greater Sydney region can be attributed to emissions from NSW’s eight coal-fired power stations” - ANSTO

https://www.ansto.gov.au/our-science/projects/aerosol-sampling-program/highlights-aerosol-sampling

Emerging application: Food Provenance

O^{18} isotopes found in shells/bones used as a 'tracer'

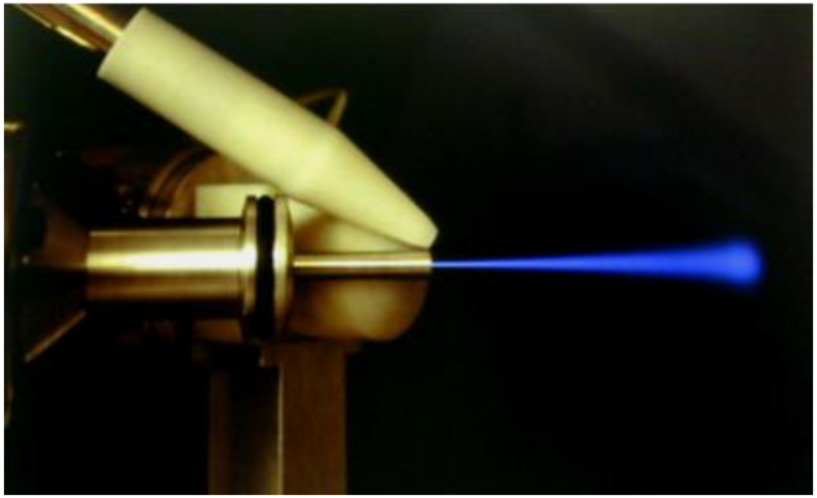




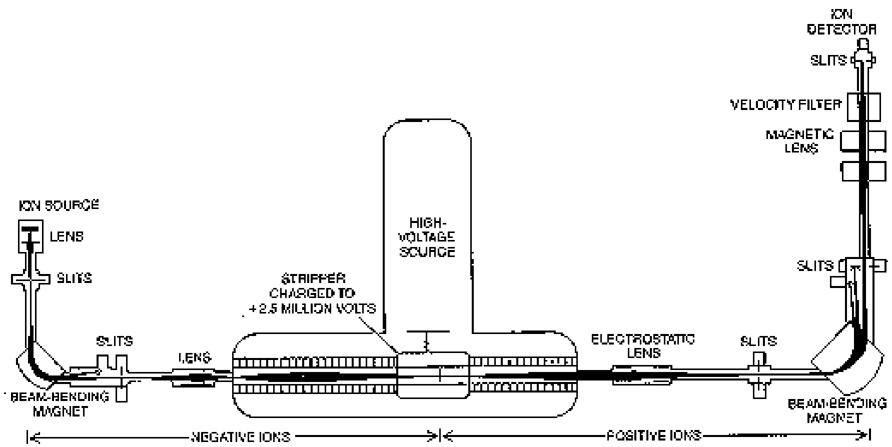
4. Historical and cultural applications

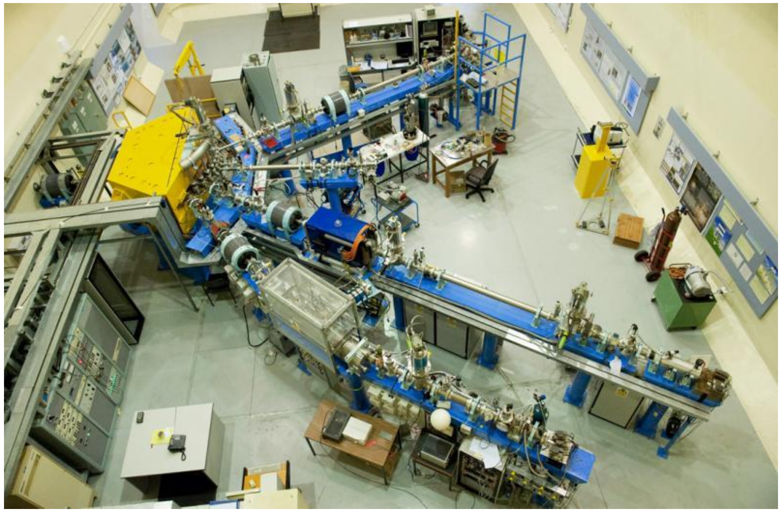
IBA techniques in art

- 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

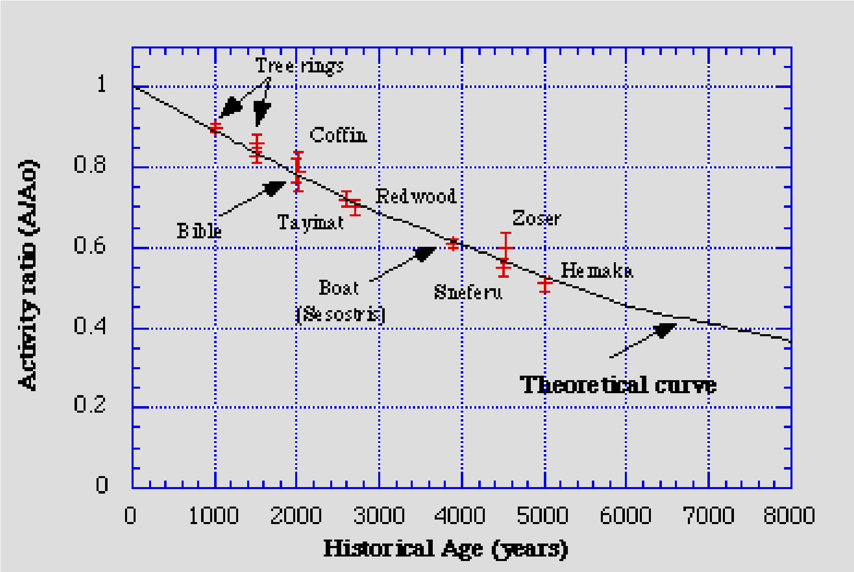


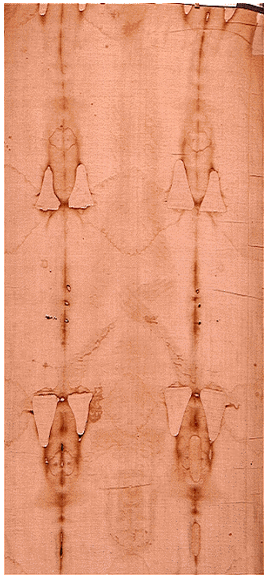
Accelerator Mass Spectrometry: Radiocarbon Dating





For more accuracy, isolate C-14 from other isotopes
"AMS" = Accelerator Mass Spectrometry

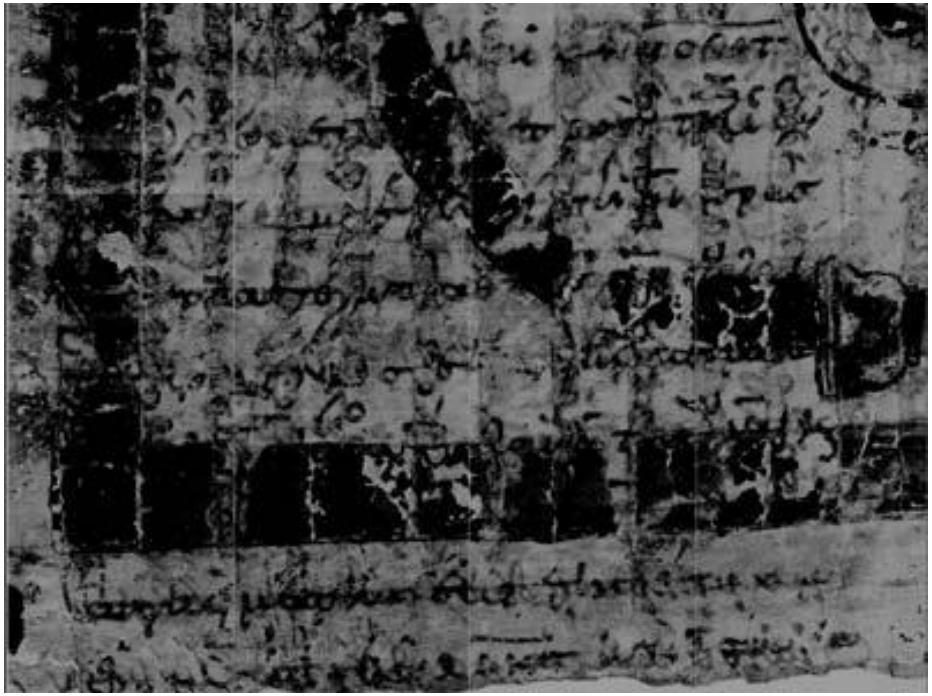




Archaeology/Heritage

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.



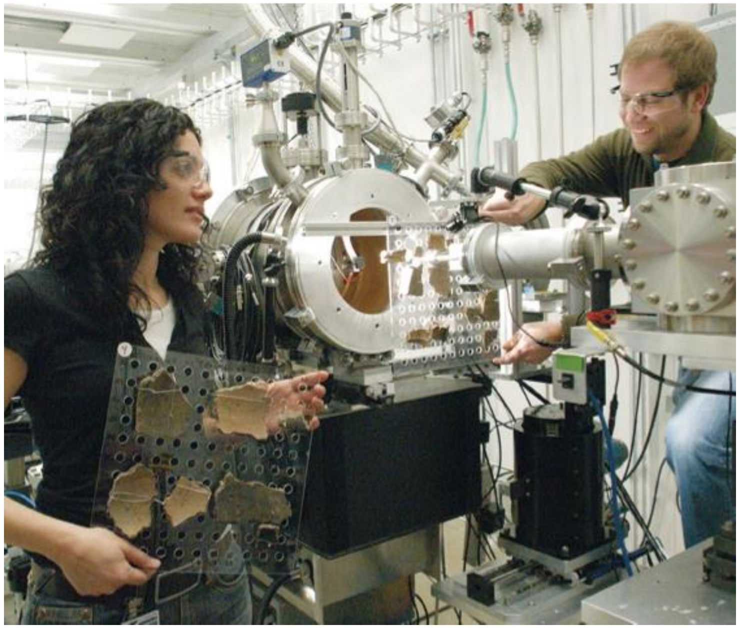
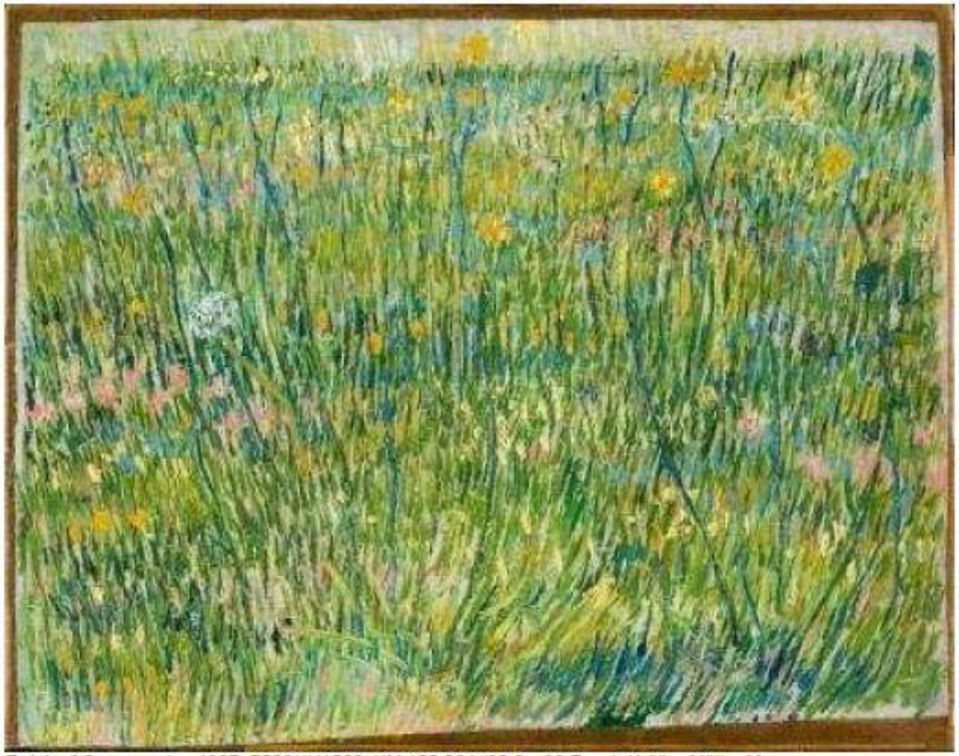


Image: Argonne National Laboratory

Pottery from Armenia, dating back to 1300 BC, is set up for a synchrotron experiment: accelerators have the advantage of being non-destructive

X-rays also used to study art

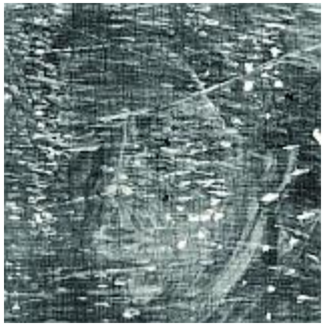


Patch of Grass, spring 1887, F583/JH1263, KM 105.264 (30,8 x 39,7 cm), Kröller-Müller Museum (Photo: Rik Klein Gotink)

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

https://www.symmetrymagazine.org/breaking/2008/07/30/particle-accelerator-reveals-hidden-van-gogh

5. Large Facilities:

Synchrotron Light Sources

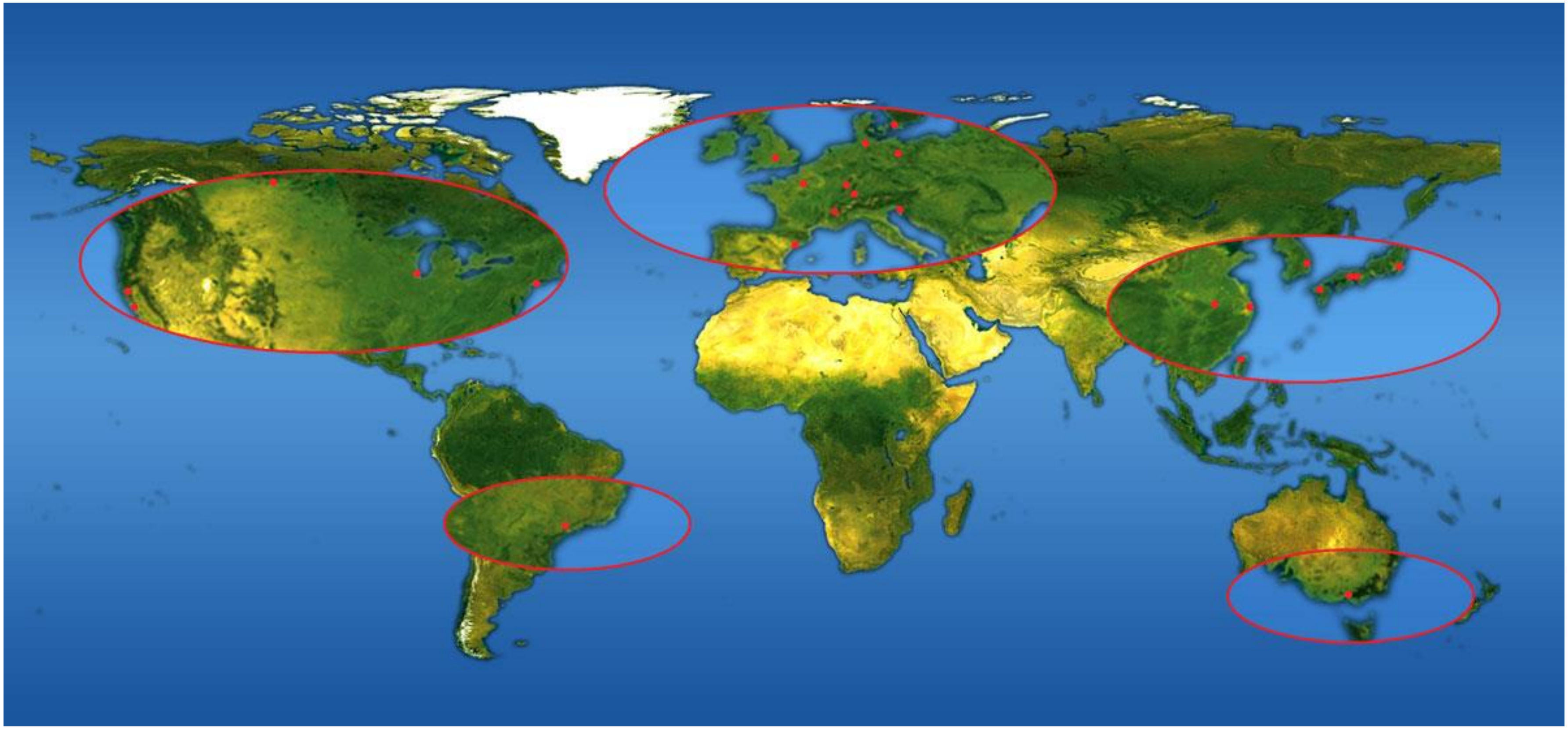
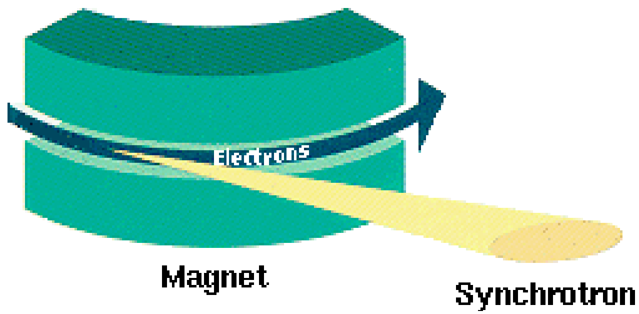
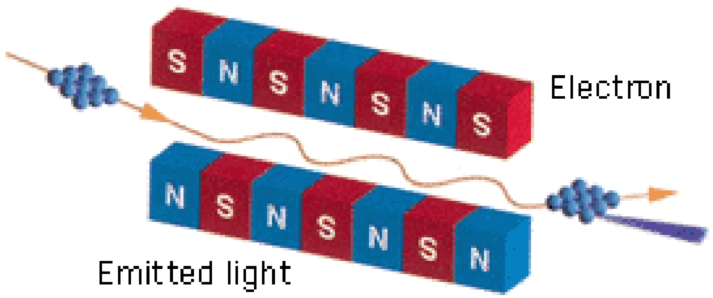
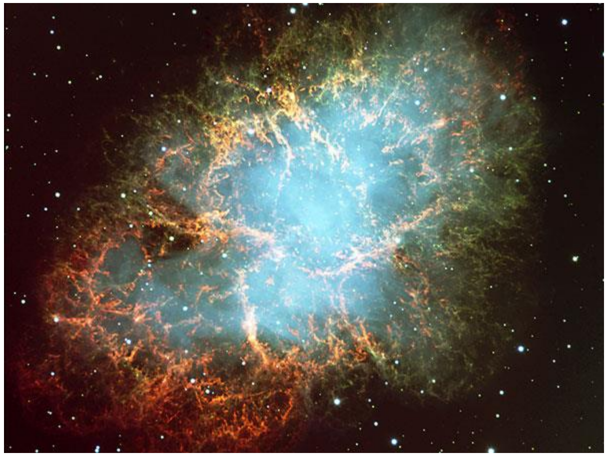


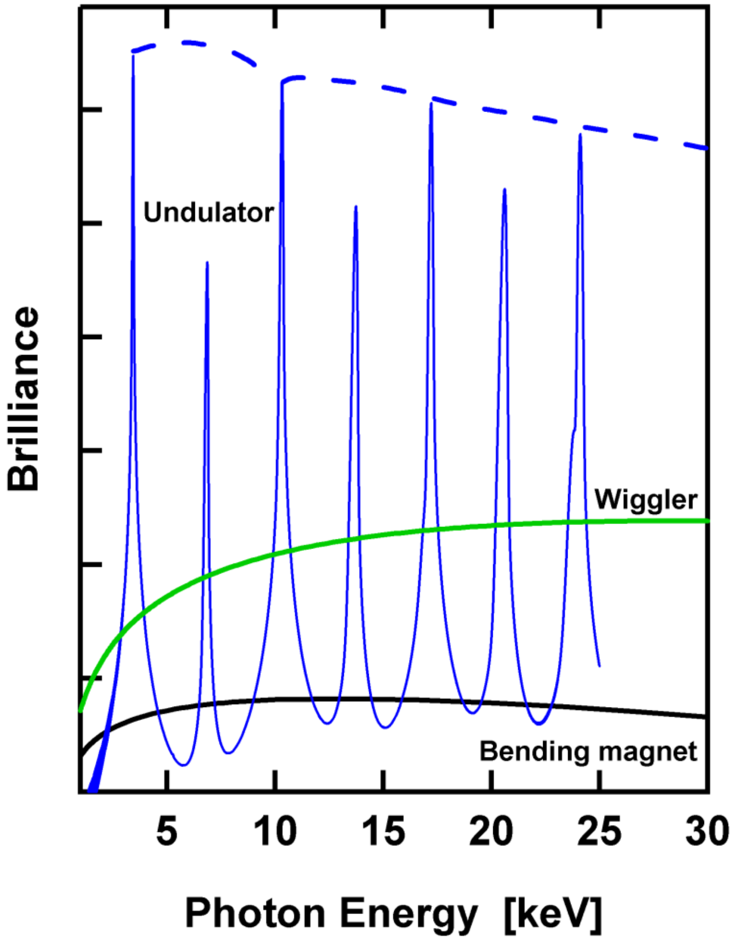
Image courtesy of ESRF

Synchrotron radiation is emitted by charged particles when accelerated radially







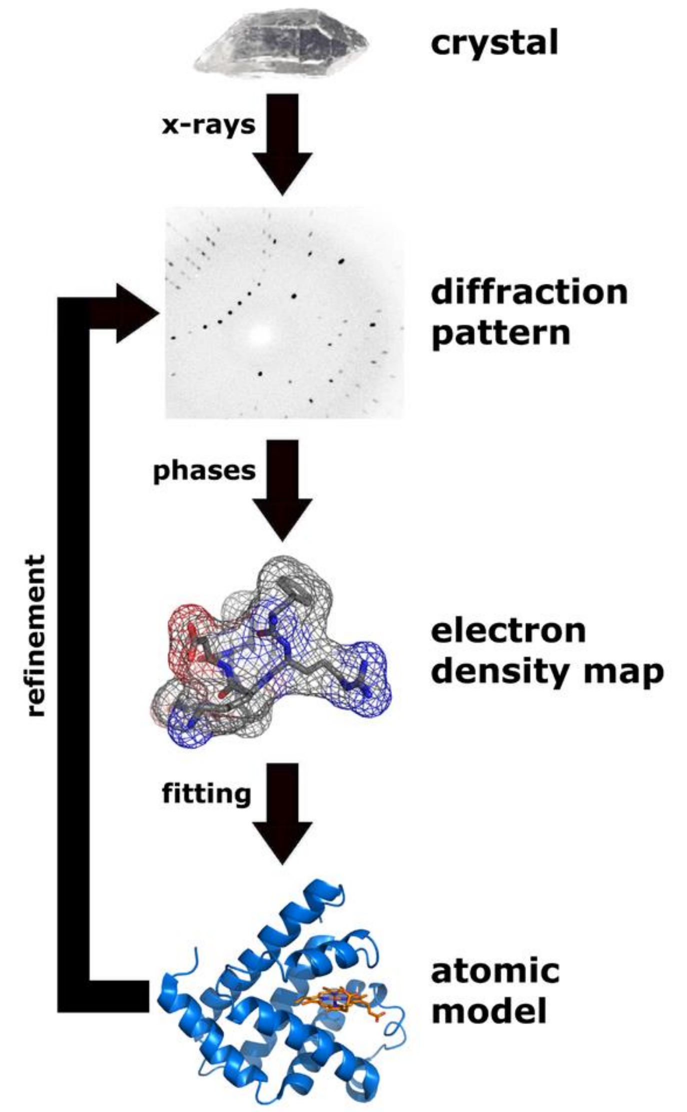


Produced in synchrotron radiation sources using bending magnets, undulators and wigglers

X-Ray crystallography

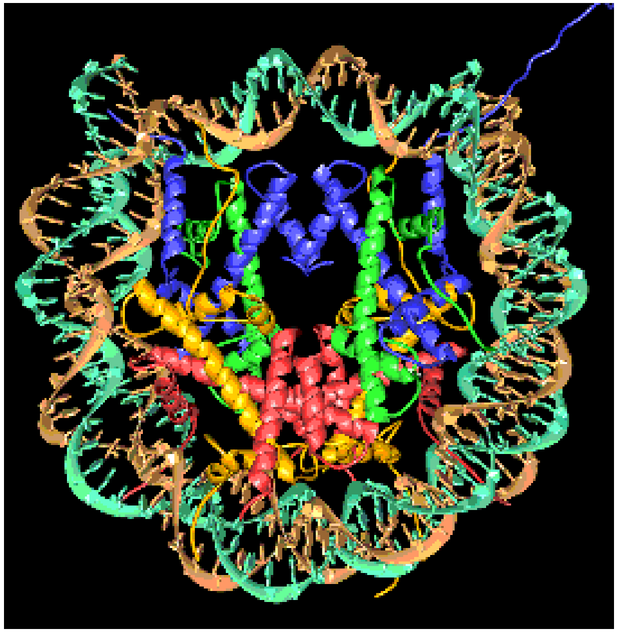
Protein crystallography is a standard technique at synchrotron light sources (Diamond light source has 5 beamlines devoted to it)

The hardest part is forming the crystal…

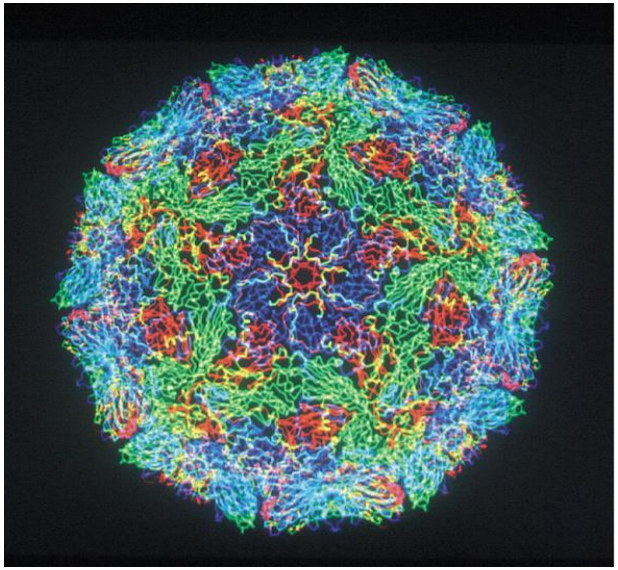


For some great overview videos of crystallography, see:
http://www.richannel.org/collections/2013/crystallography

Structural Biology

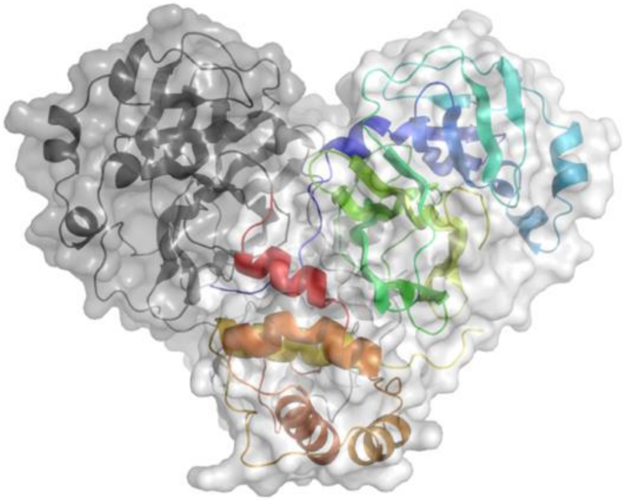


Reconstruction of the 3D structure of a nucleosome (DNA packaging) with a resolution of 0.2 nm



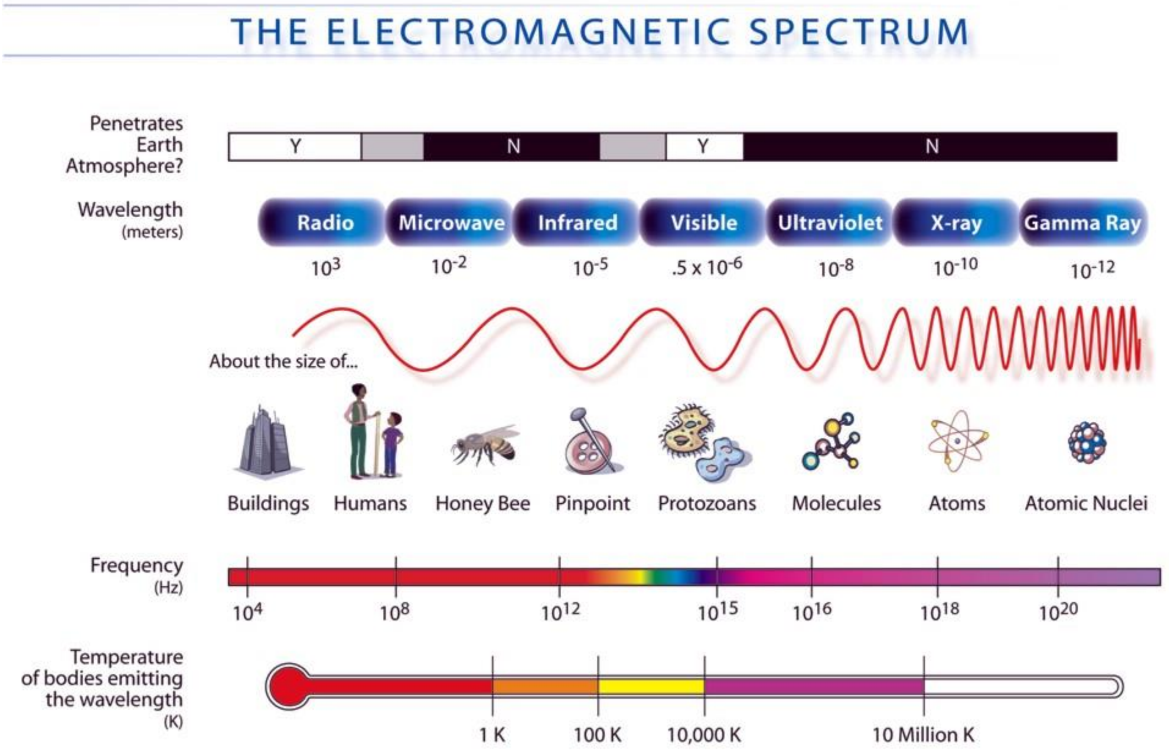
In 1990 scientists determined the structure of a strain of foot & mouth virus using Daresbury SRS.

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



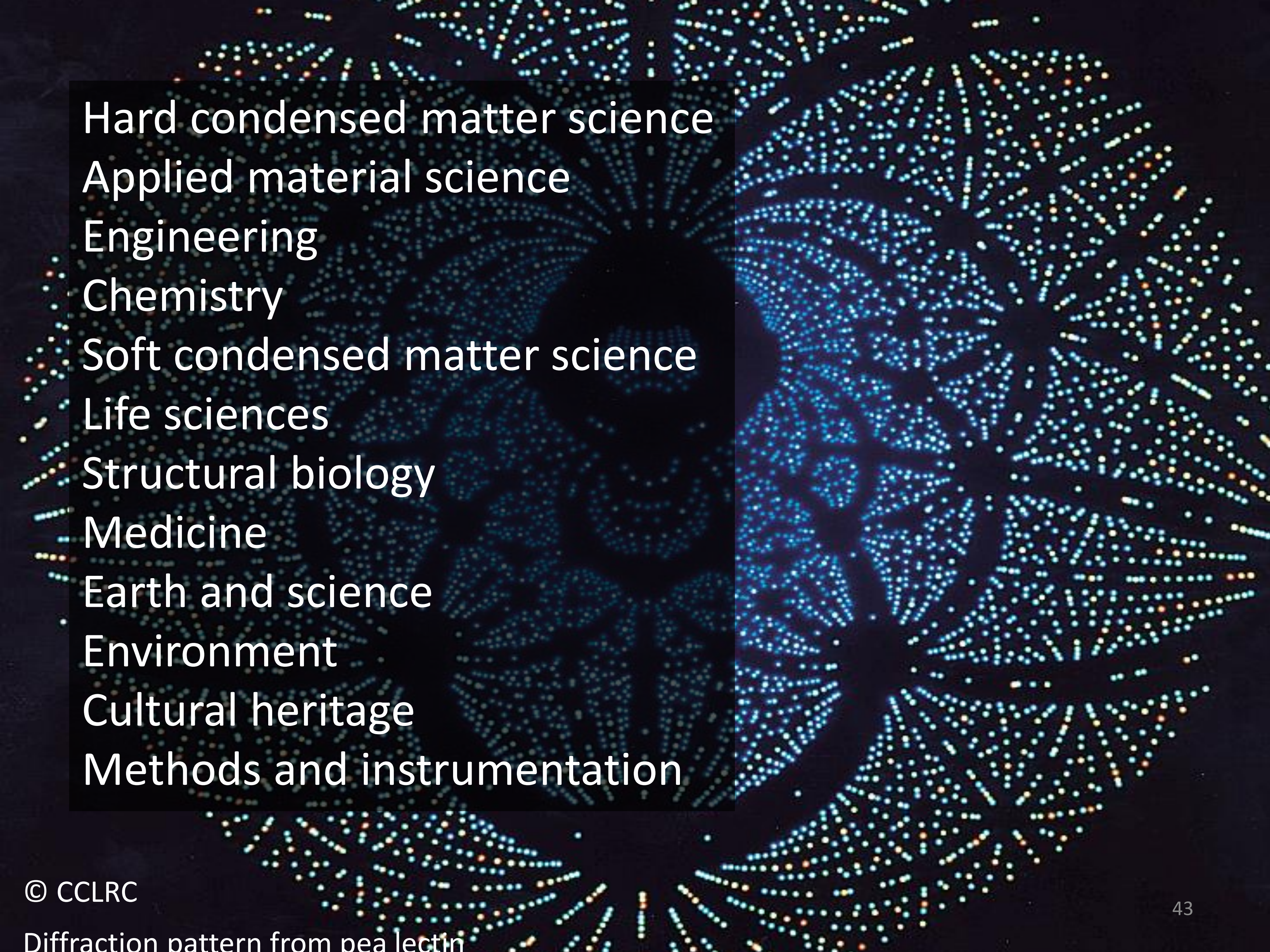
More info:
https://cerncourier.com/a/synchrotrons-on-the-coronavirus-frontline/

- 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)

Hard condensed matter science
Applied material science
Engineering
Chemistry
Soft condensed matter science
Life sciences
Structural biology
Medicine
Earth and science
Environment
Cultural heritage
Methods and instrumentation



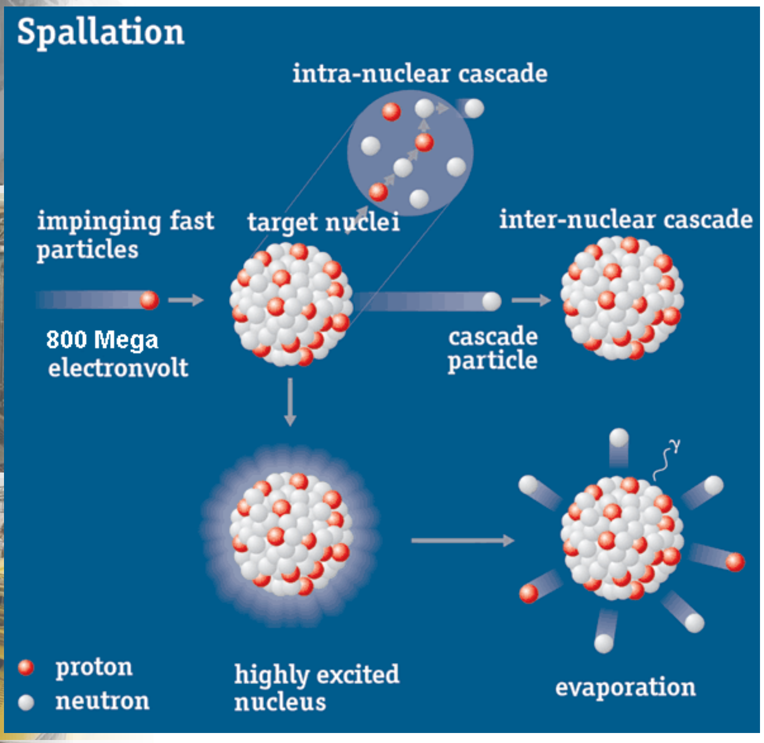
Diffraction pattern from pea lectin

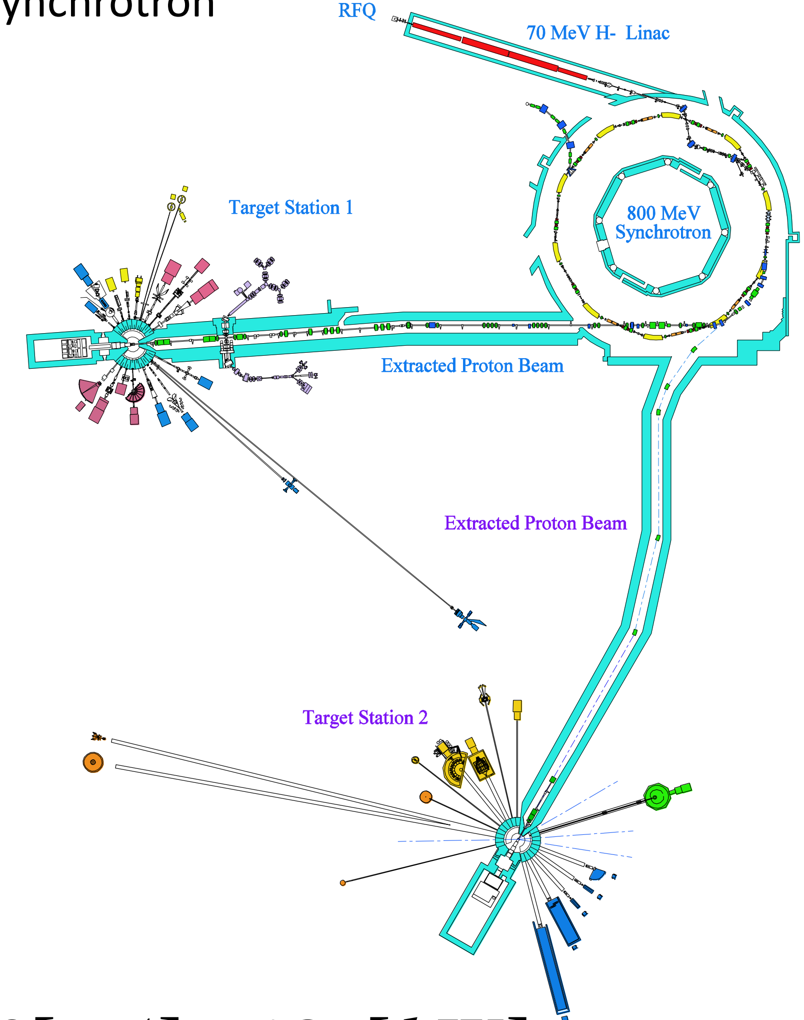
5. Large Facilities

Neutron Spallation Sources

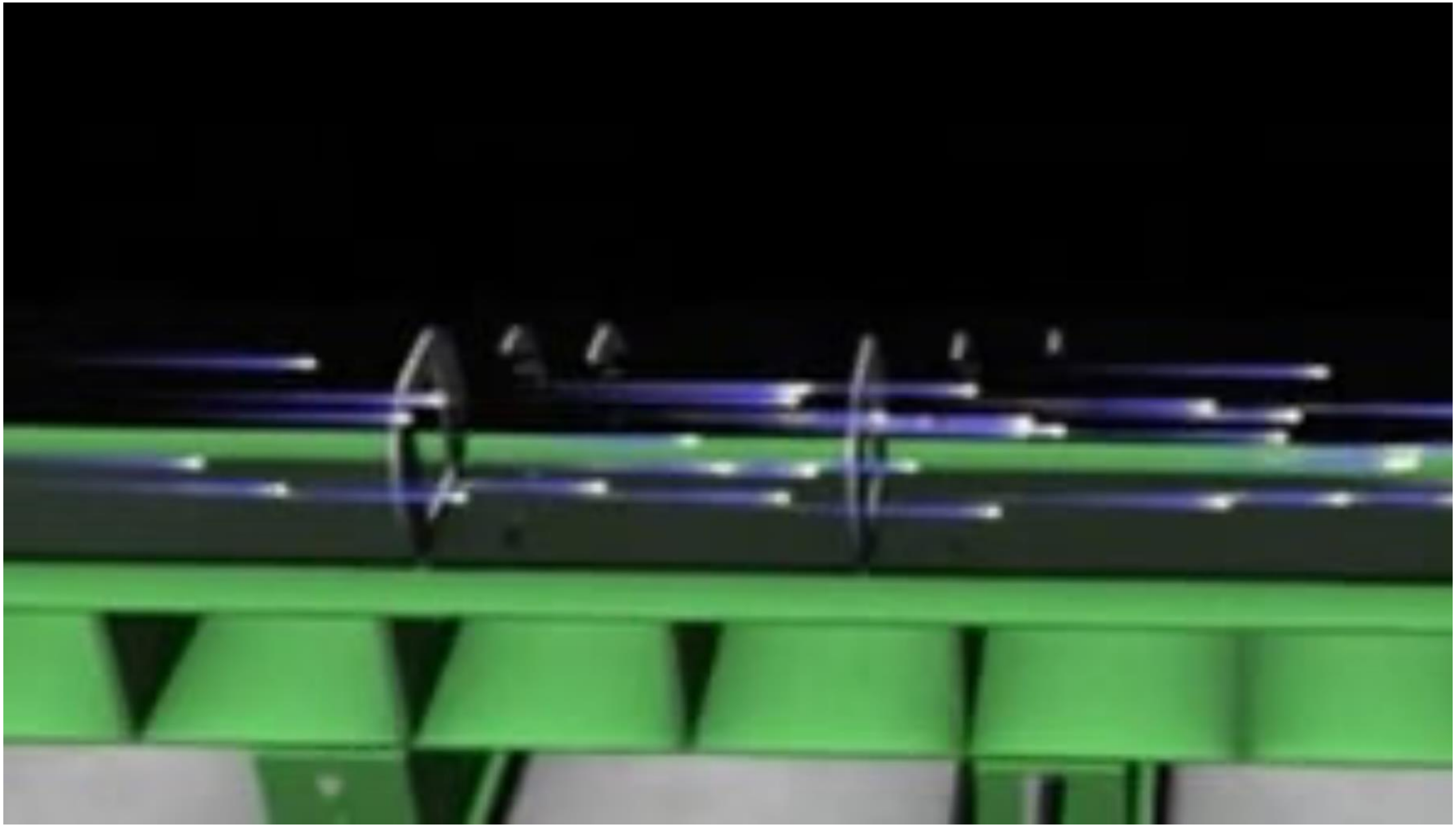
From Protons to Neutrons: Spallation Sources

Example: UK's STFC ISIS neutron spallation source:
RFQ + linac + 800 MeV proton synchrotron



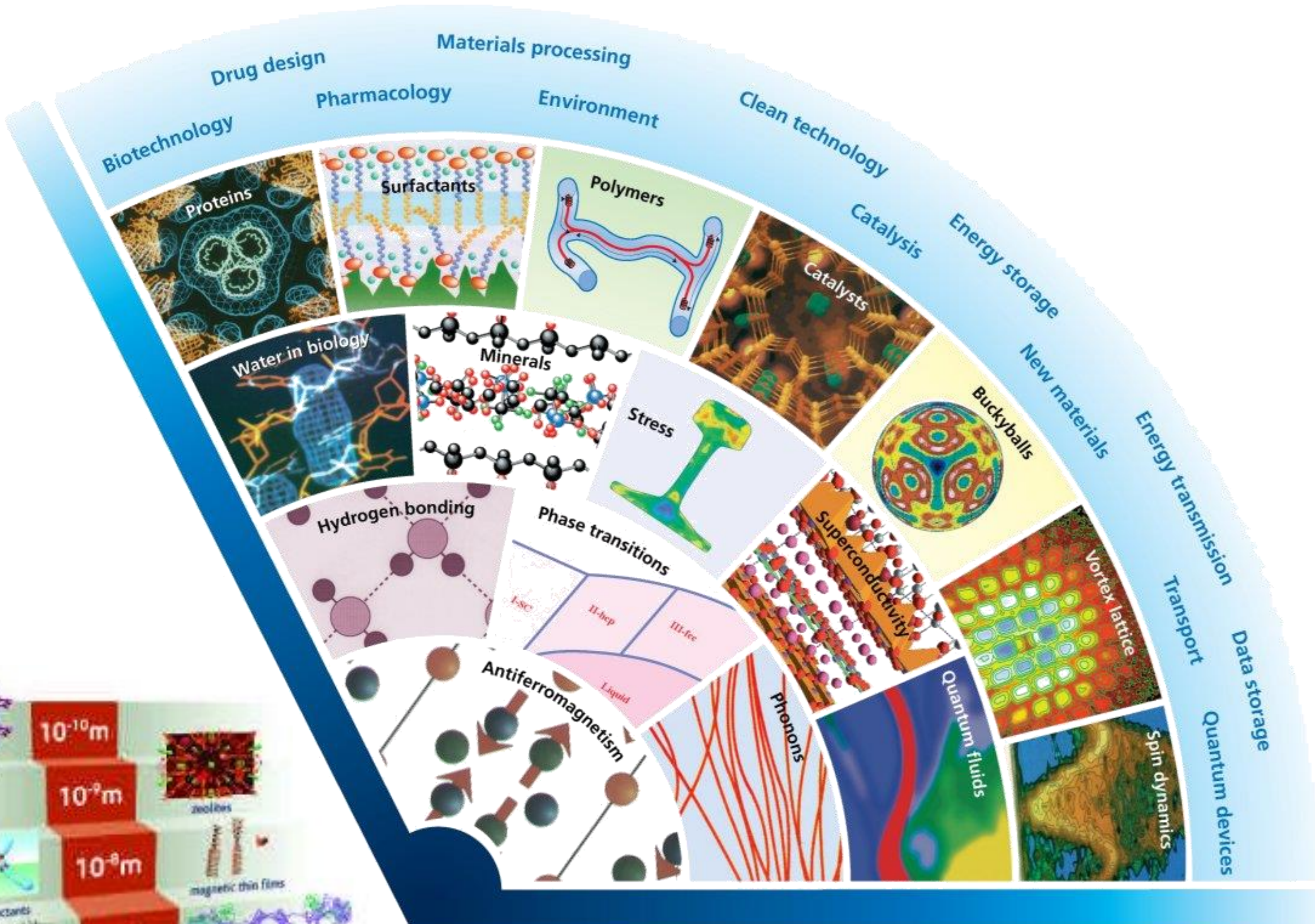


$$P = 800[MV] \times 230[\mu A] = 184[kW]$$



https://youtu.be/VESMU7JfVHU?t=21

‘Neutrons tell you where atoms ***are*** and what atoms ***do***’



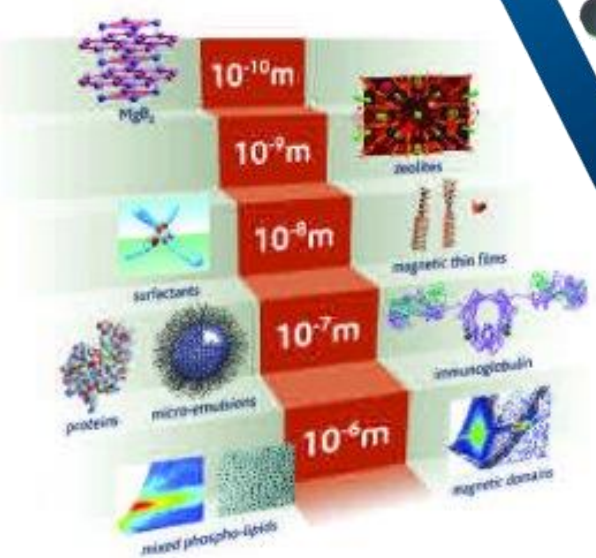
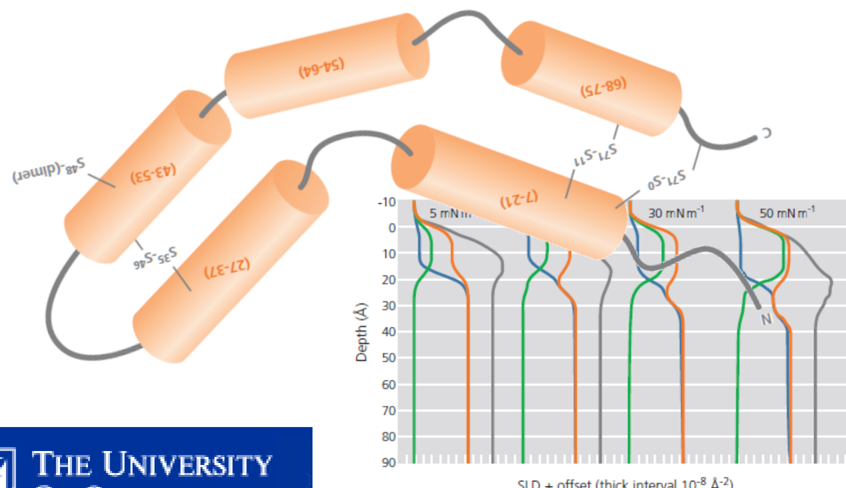


Image courtesy ISIS, STFC.

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

THE UNIVERSITY OF QUEENSLAND
AUSTRALIA

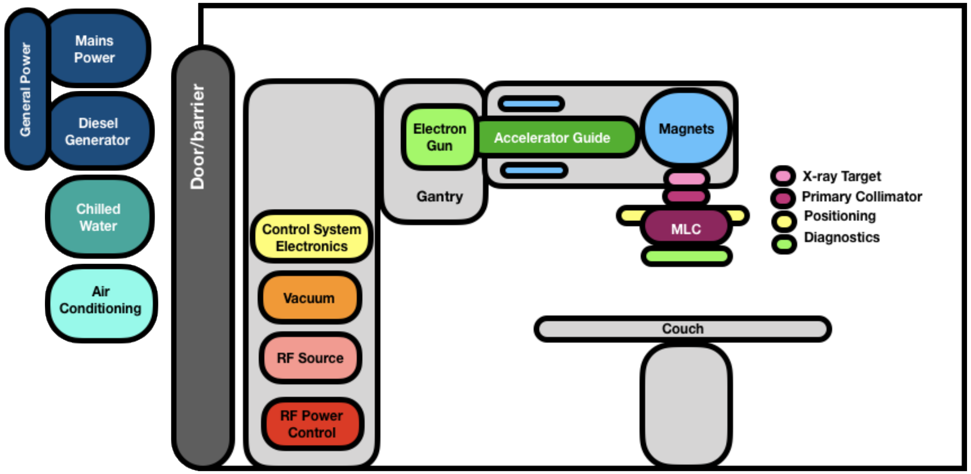
6. Future Challenges

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

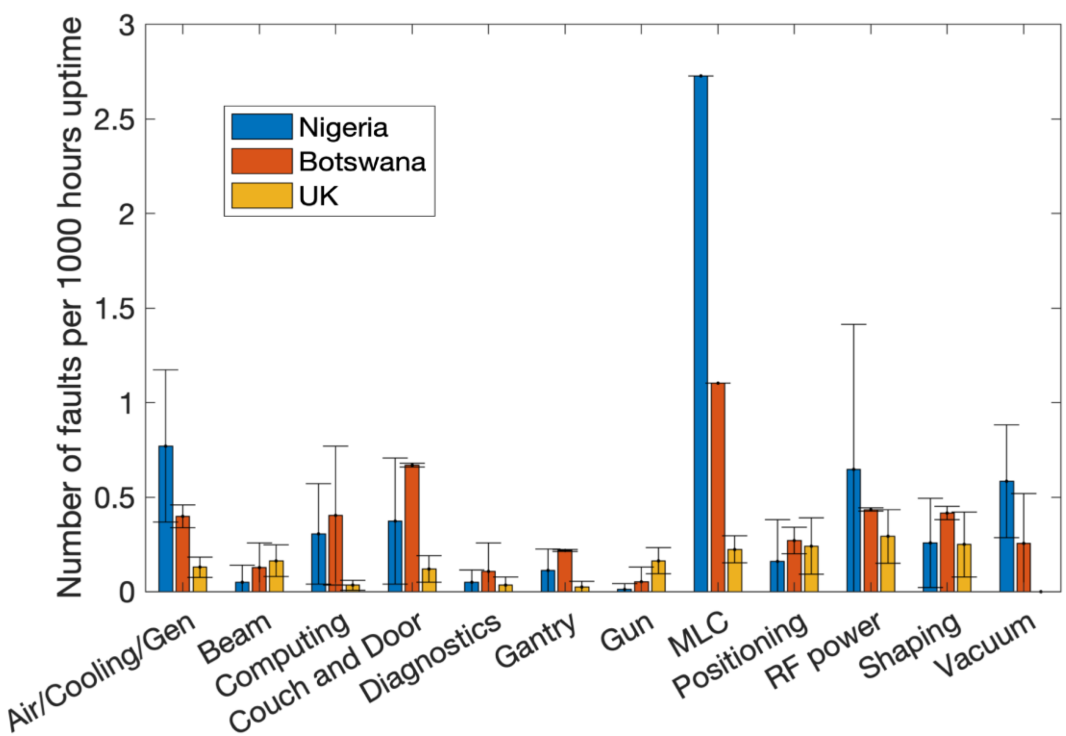
The Reliability Frontier



ELSEVIER
Clinical Oncology
Volume 32, Issue 4, April 2020, Pages e111-e118
Original Article

Comparative Analysis of Radiotherapy Linear Accelerator Downtime and Failure Modes in the UK, Nigeria and Botswana

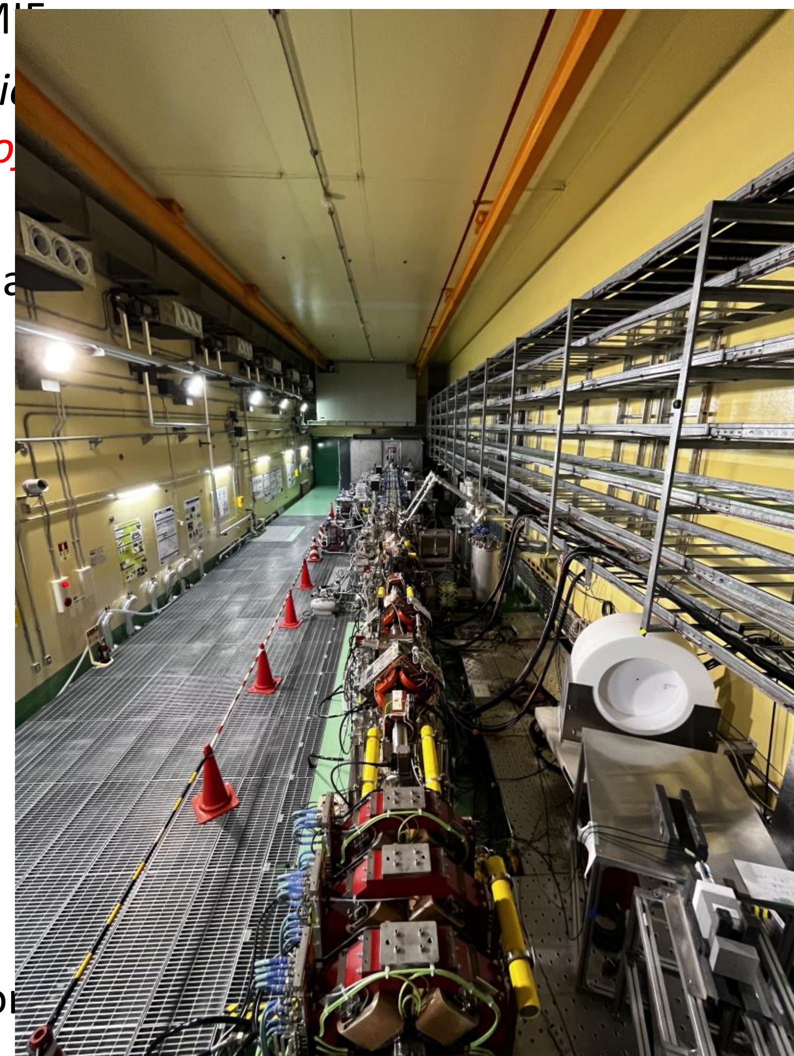
L.M. Wroe *, T.A. Ige †, O.C. Asogwa †, S.C. Aruah †, S. Grover ‡, R. Makufa §, M. Fitz-Gibbon ¶, S.L. Sheehy *



Intensity Frontier:

Materials testing for fusion

40
2 x
CW
Be
To
rea



Intensity Frontier:
Accelerator Driven Systems

Transmutation of nuclear waste isotopes or energy generation

Thorium

Major challenges for accelerator technology in terms of beam power (>10MW) and reliability

https://myrrha.be/about-myrrha

Sustainability Frontier

Environmental Impacts

- Electrical power
  - Electromagnets → permanent magnets?
  - Energy recovery linacs
  - High temperature superconductors
- Materials
  - Rare metals often *required*
- Gases:
  - SF6, HFC, PFC tightly controlled
- Recycle-ability?
- Impacts on residents esp. indigenous populations

The SESAME facility has its own solar power plant

Credit: CARABAN GONZALEZ, NOEMI / CERN / SCIENCE PHOTO LIBRARY

https://www.nature.com/articles/s41567-023-02117-0

A challenge to you:

What is the most ‘surprising’ application of an accelerator you can think of?