Applications of Accelerators

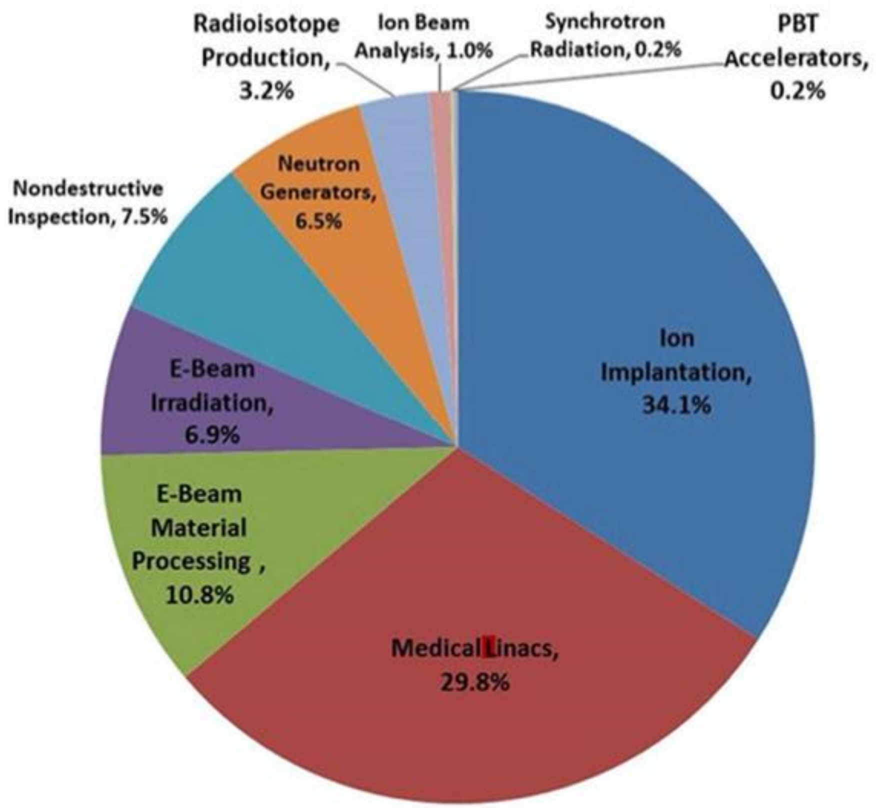
CERN Introductory Accelerator School
Geneva, 2021

Dr. Suzie Sheehy

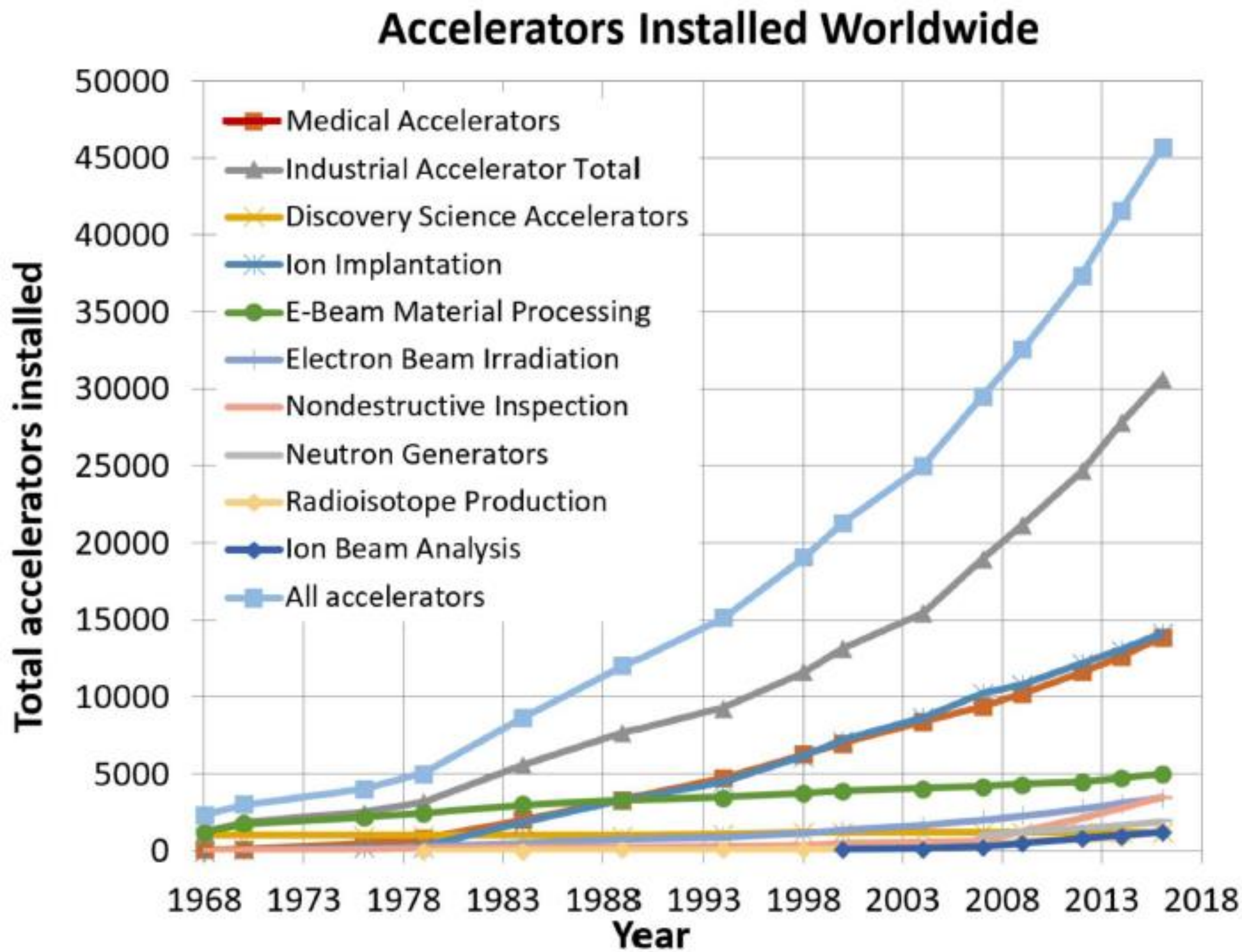
Senior Lecturer, University of Melbourne

Royal Society University Research Fellow, University of Oxford

"A beam of particles is a very useful tool..."



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

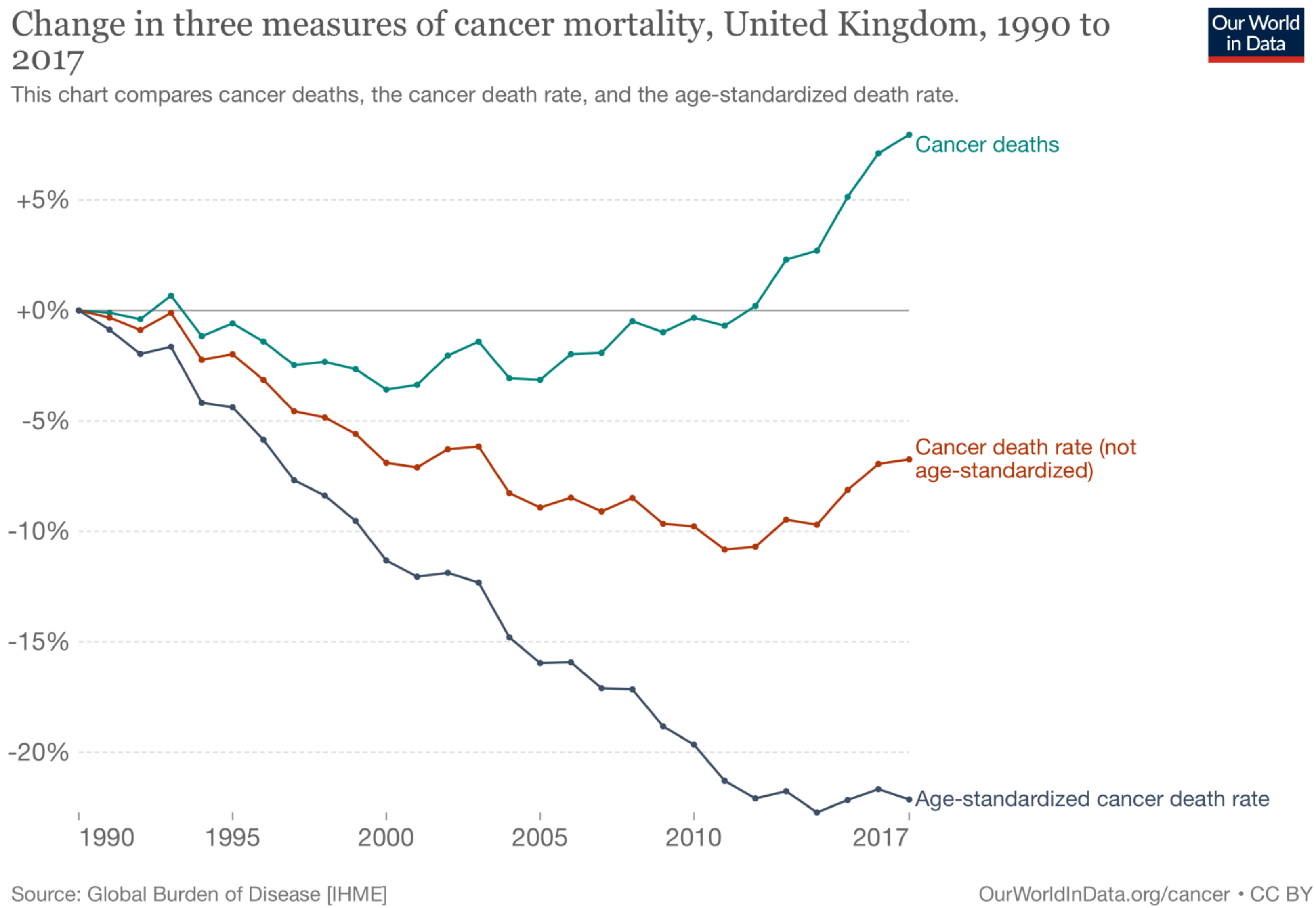


Doyle, McDaniel, Hamm, *The Future of Industrial Accelerators and Applications, SAND2018-5903B*

Outline

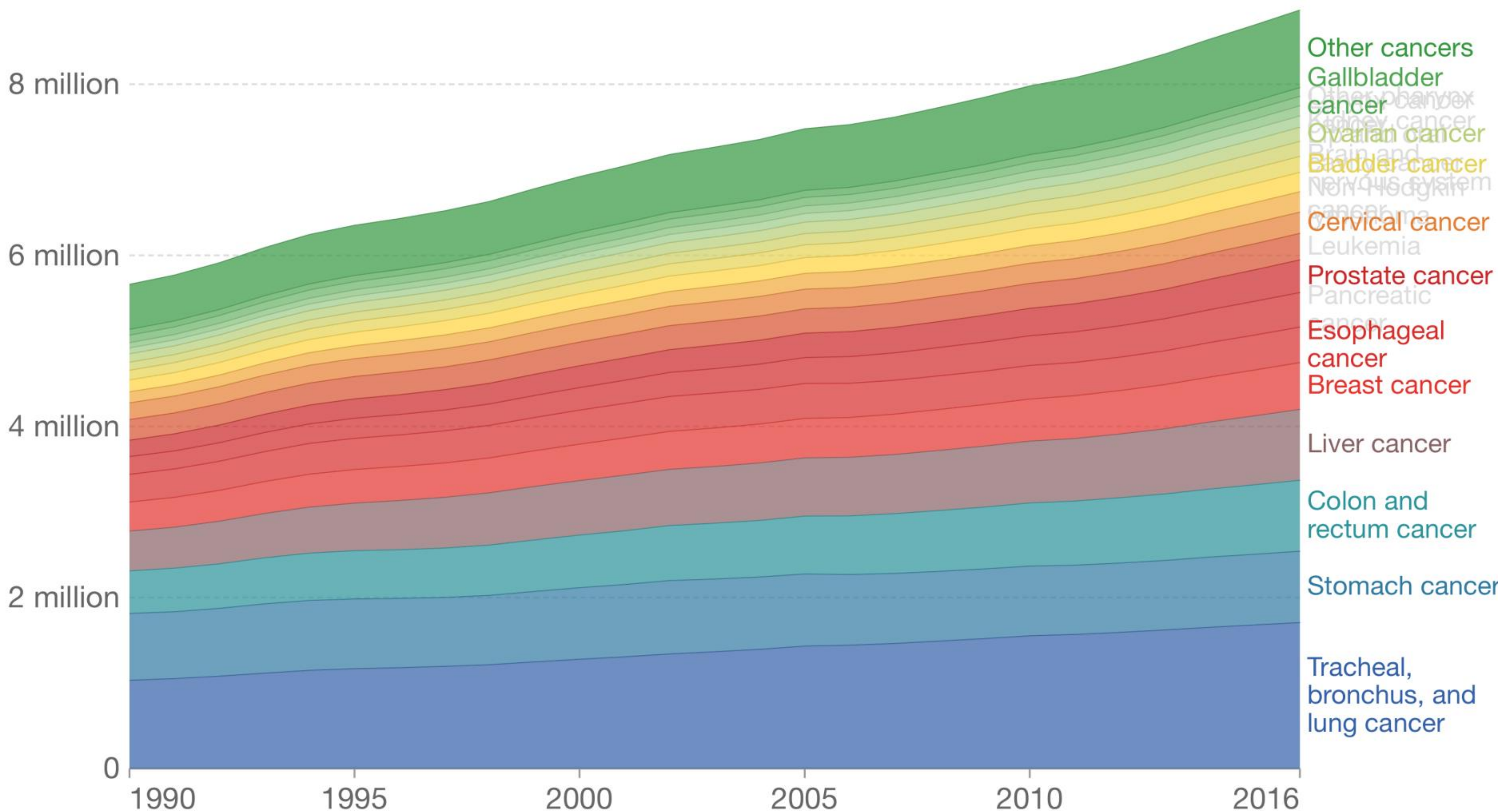
1. Medical imaging and treatment
2. Industrial uses of accelerators
3. Synchrotron light sources
4. Neutron sources
5. Energy, environment & security applications
6. Historical & cultural applications

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.
Our World in Data
Cancer deaths
Cancer death rate (not age-standardized)
Age-standardized cancer death rate
+5%
+0%
-5%
-10%
-15%
-20%
1990
1995
2000
2005
2010
2017
Source: Global Burden of Disease [IHME]
OurWorldInData.org/cancer • CC BY

Cancer deaths by type, World, 1990 to 2016

Annual cancer deaths by cancer type, measured as the total number of deaths across all age categories and both sexes. Smaller categories of cancer types with global deaths <100,000 in 2016 have been grouped into a collective category 'Other cancers'. See sources for list of grouped cancers.



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)

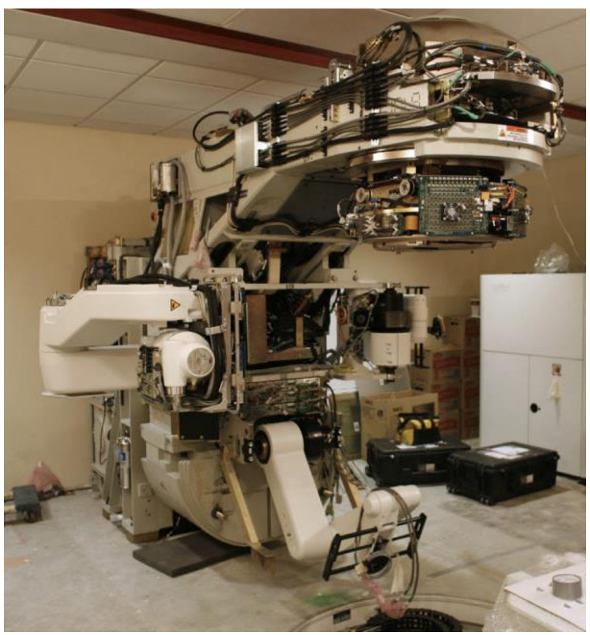
Around **half of all cancer patients** in HICs benefit from RT

Linac (S-band)

Achromatic Bend

Foil to produce x-rays

Collimation system



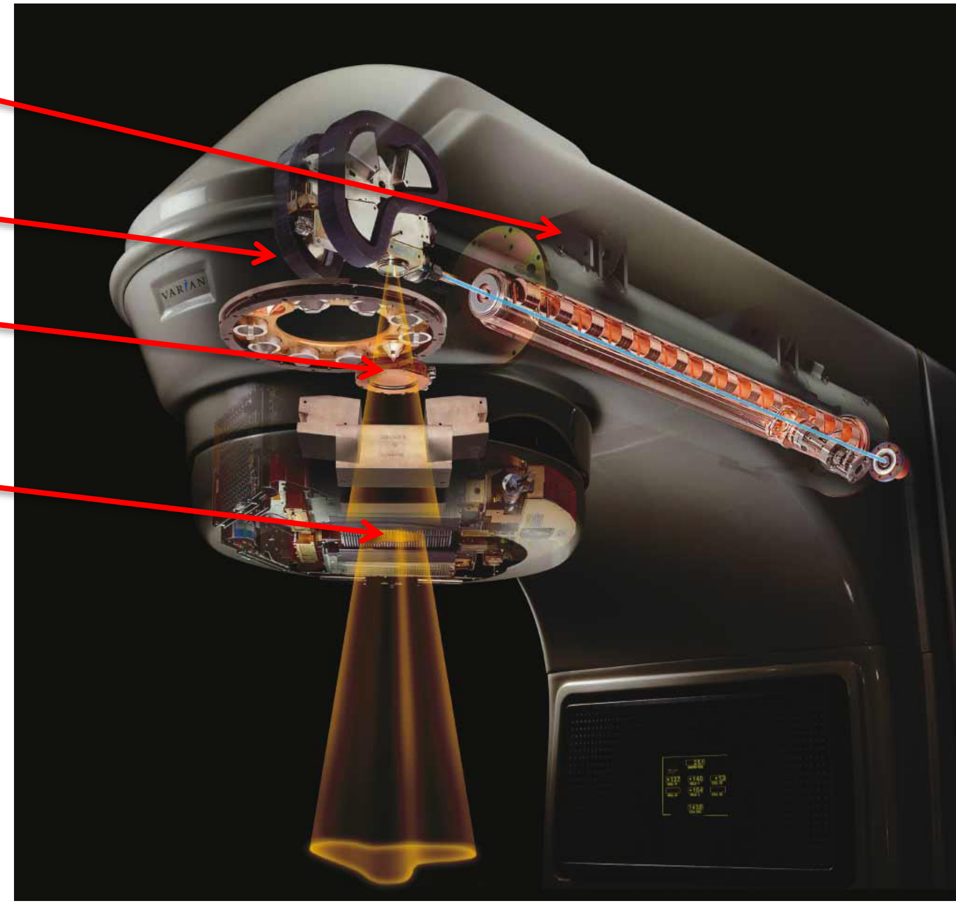
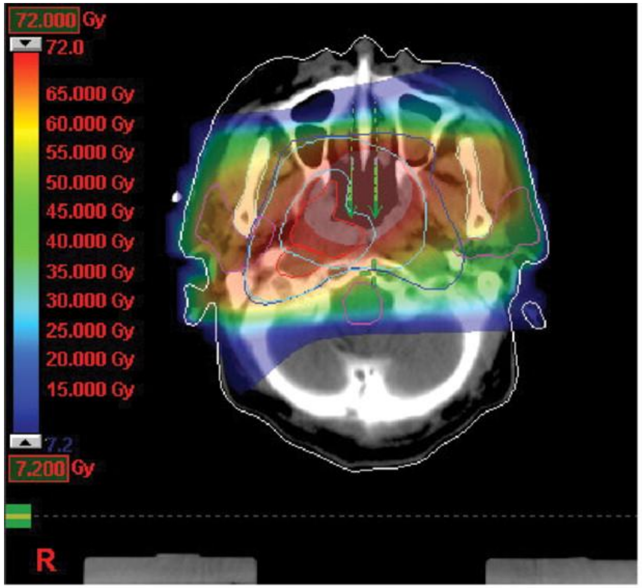
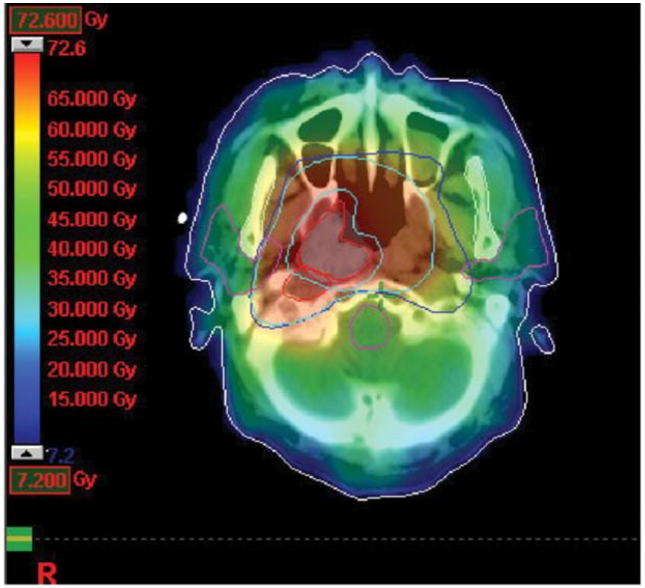


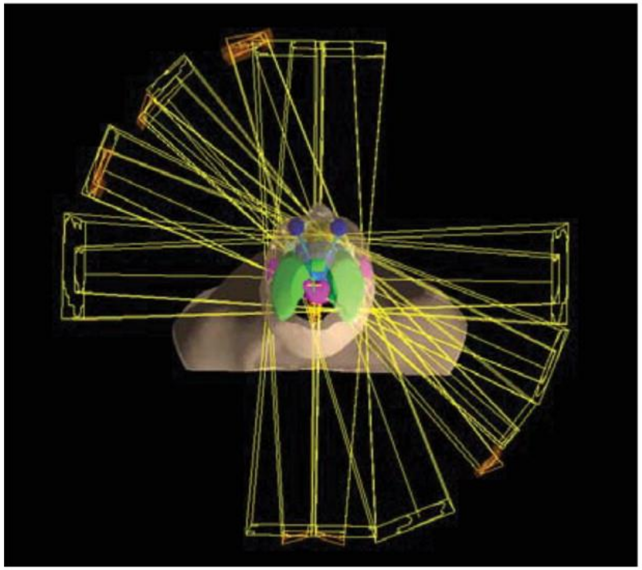
Image: copyright Varian medical systems


72.000 Gy
72.0
65.000 Gy
60.000 Gy
55.000 Gy
50.000 Gy
45.000 Gy
40.000 Gy
35.000 Gy
30.000 Gy
25.000 Gy
20.000 Gy
15.000 Gy
7.2
7.200 Gy
R

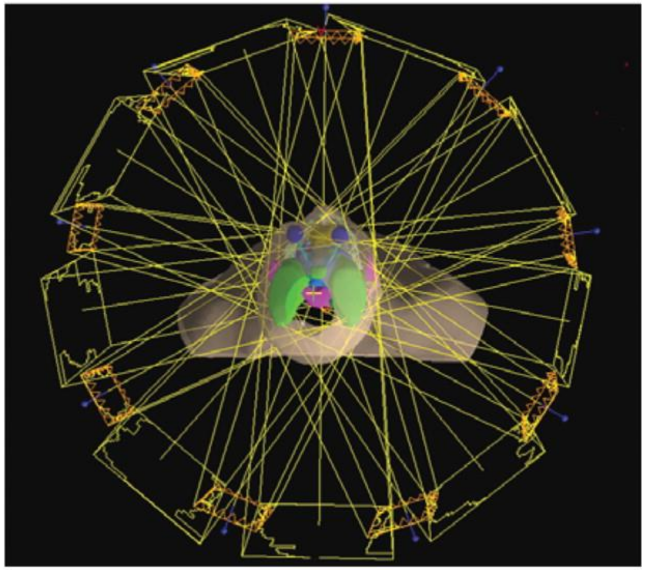
(a)


72.600 Gy
72.6
65.000 Gy
60.000 Gy
55.000 Gy
50.000 Gy
45.000 Gy
40.000 Gy
35.000 Gy
30.000 Gy
25.000 Gy
20.000 Gy
15.000 Gy
7.2
7.200 Gy
R

(b)



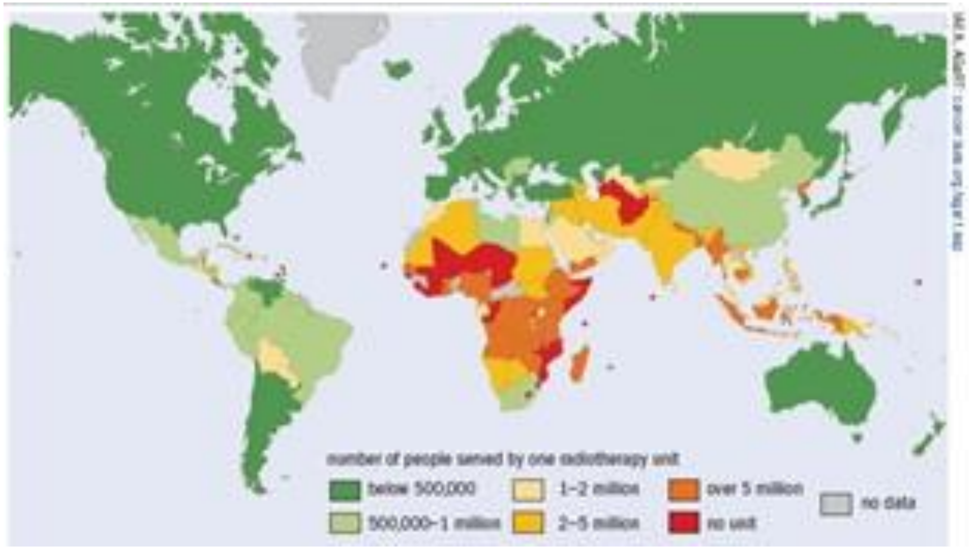
(c)



(d)

A Global Challenge in Healthcare:

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

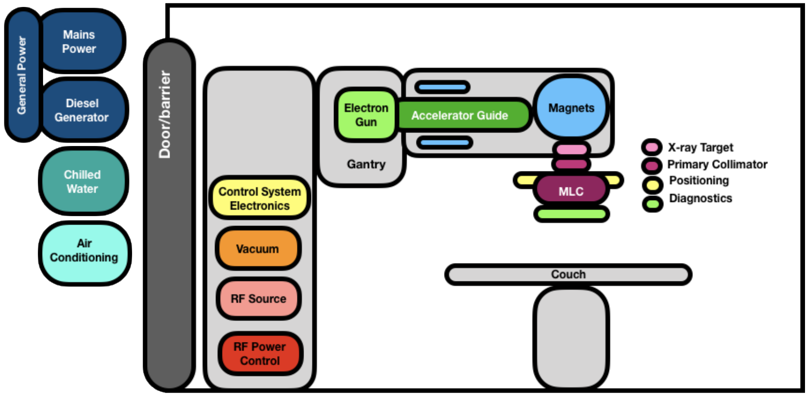


International Cancer Expert Corps

Partnering to transform global cancer care

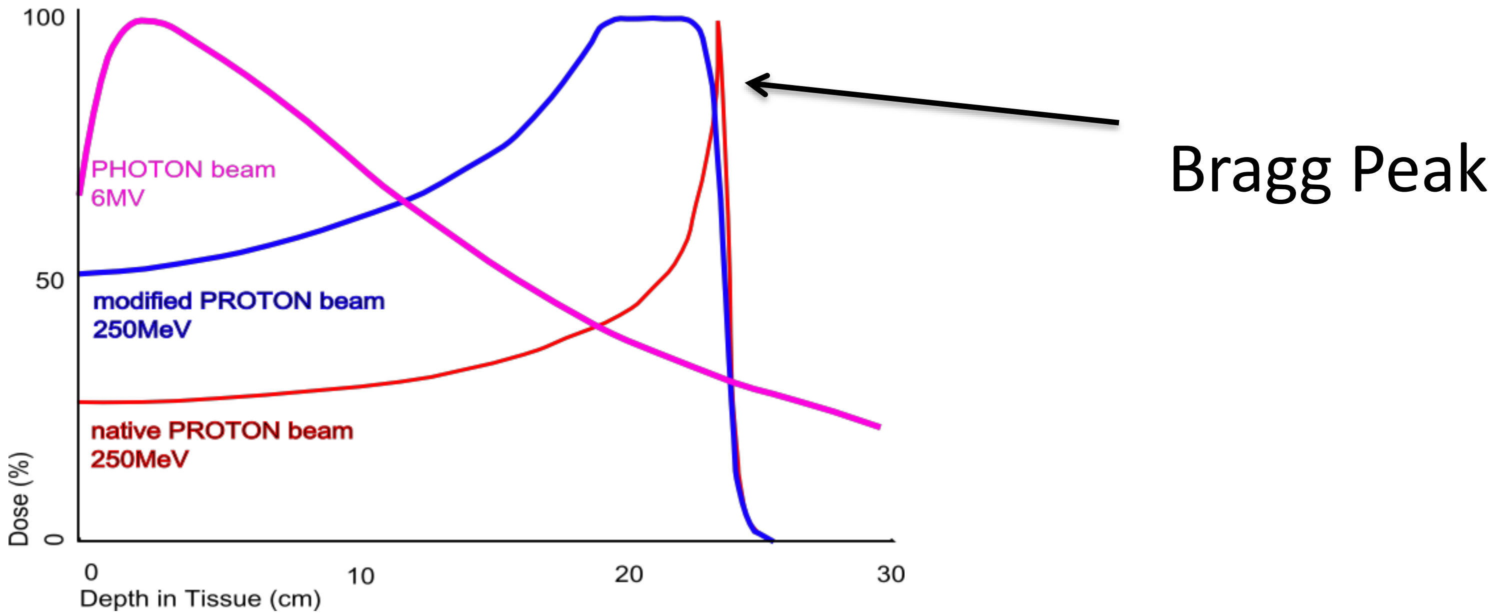
UKRI Science and Technology Facilities Council

CERN



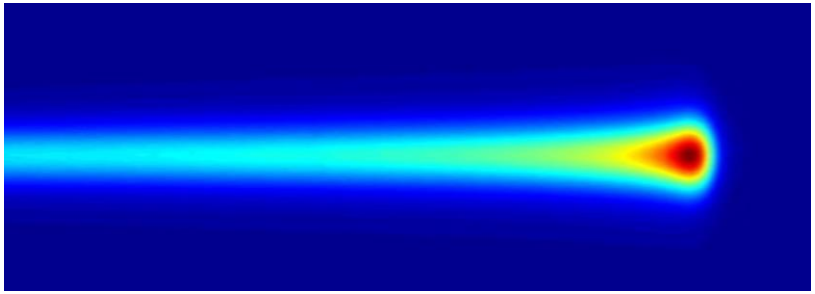
STELLA Collaboration Formed to Address this Issue

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

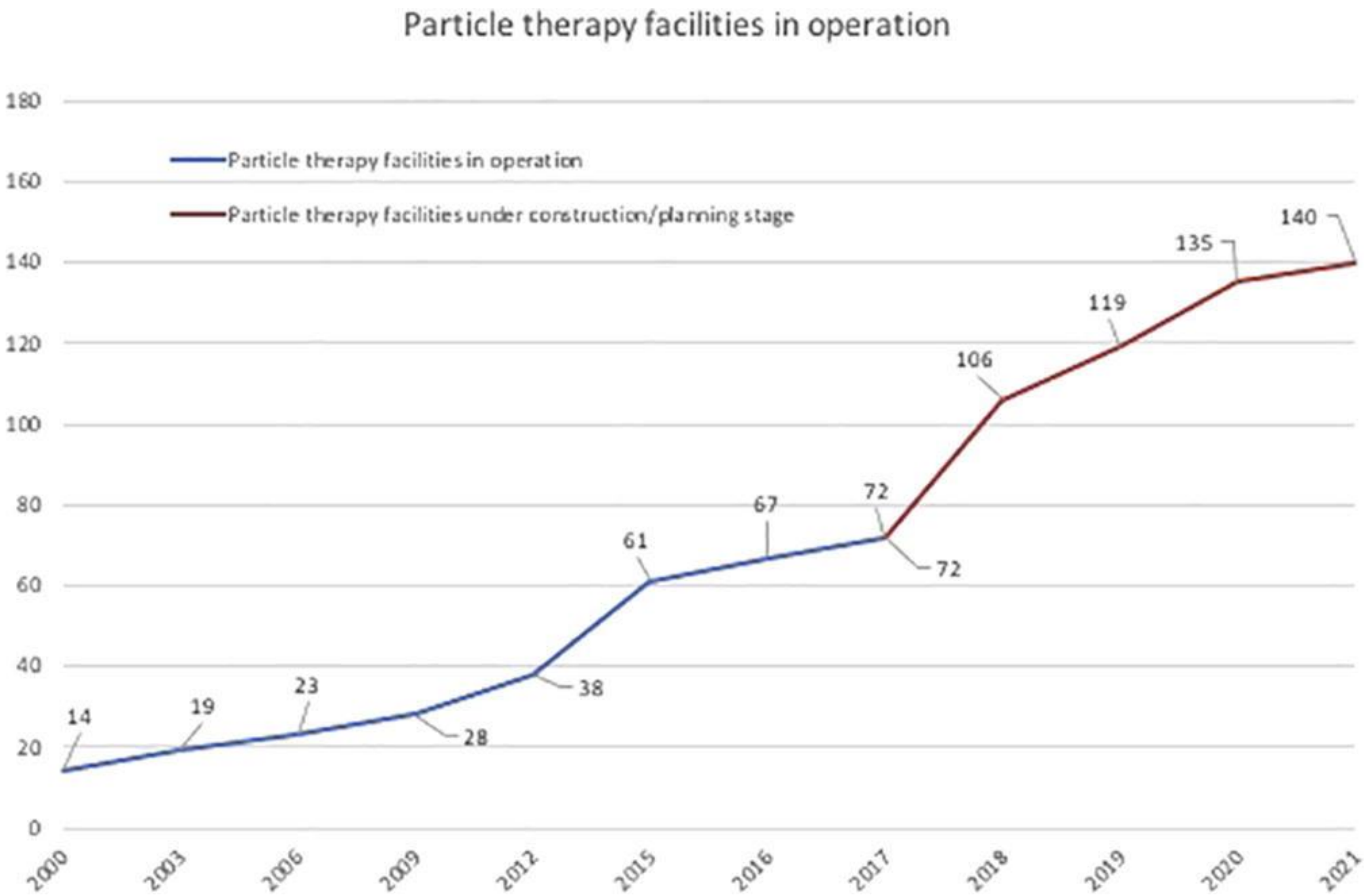
m_e rest mass of the electron

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

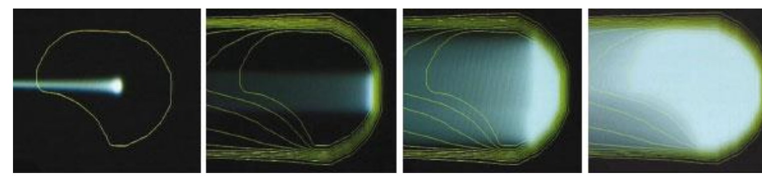
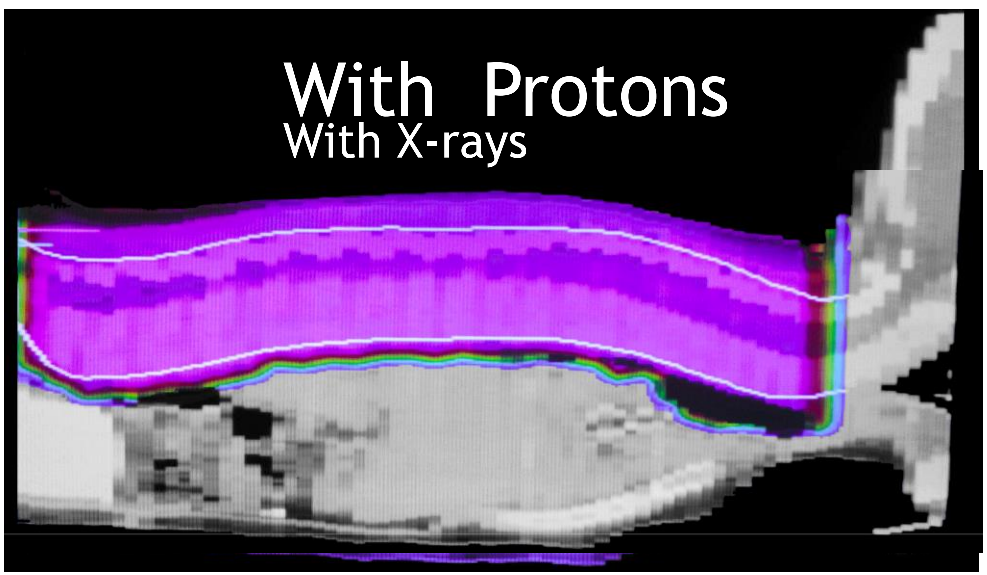


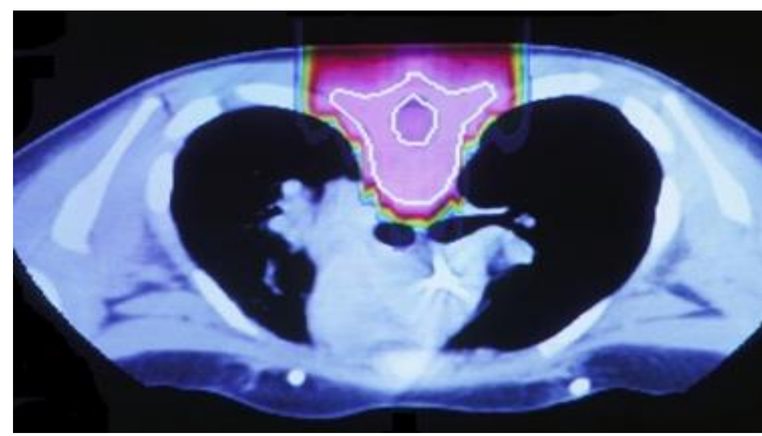
https://www.thegreenjournal.com/article/S0167-8140(18)30146-4/fulltext

Proton & Ion therapy

  - "Hadron therapy" = Protons and light ions

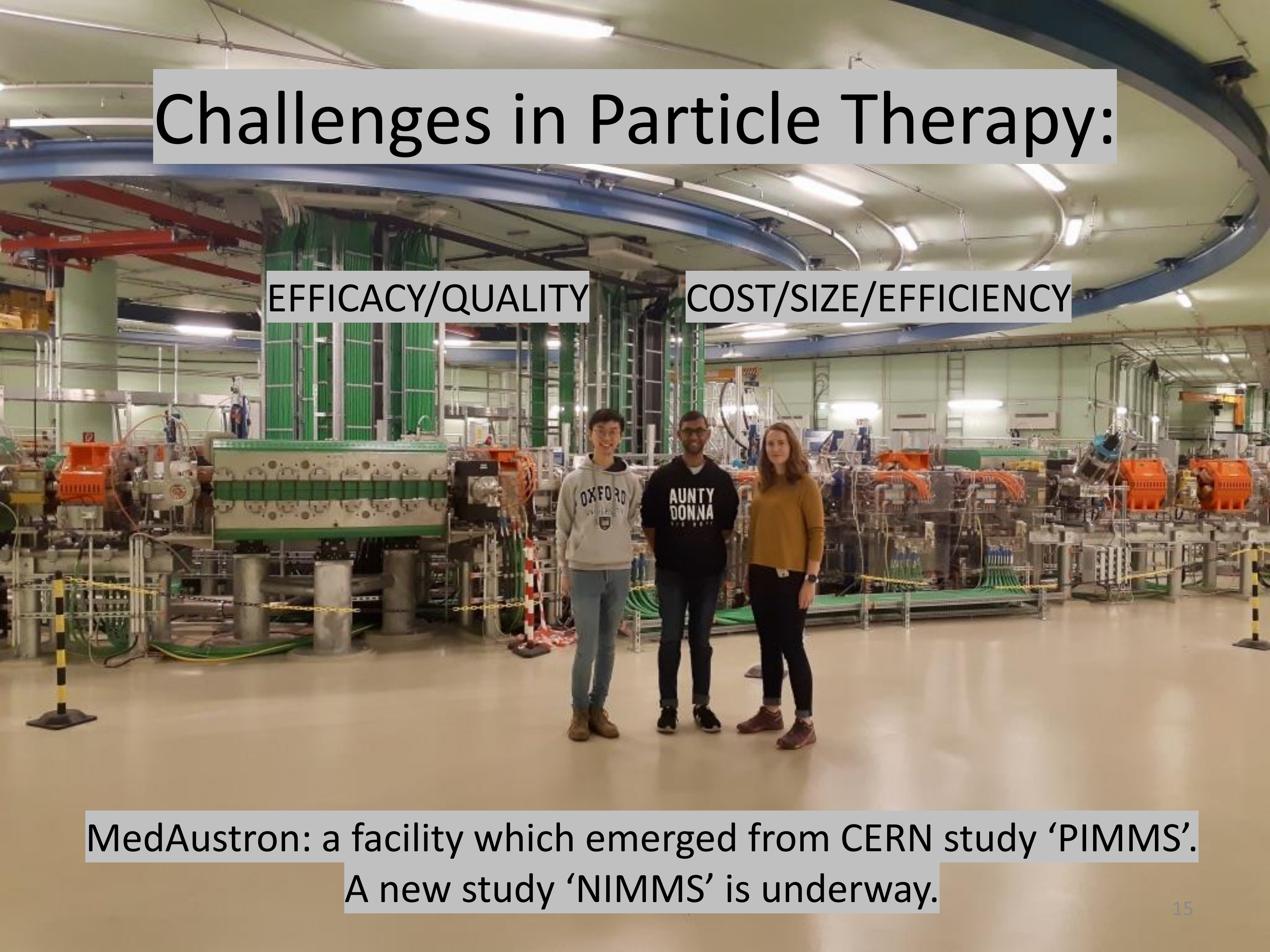
- Used to treat localised cancers
- Less morbidity for healthy tissue
- Less damage to vital organs
- Particularly for childhood cancers



Challenges in Particle Therapy:

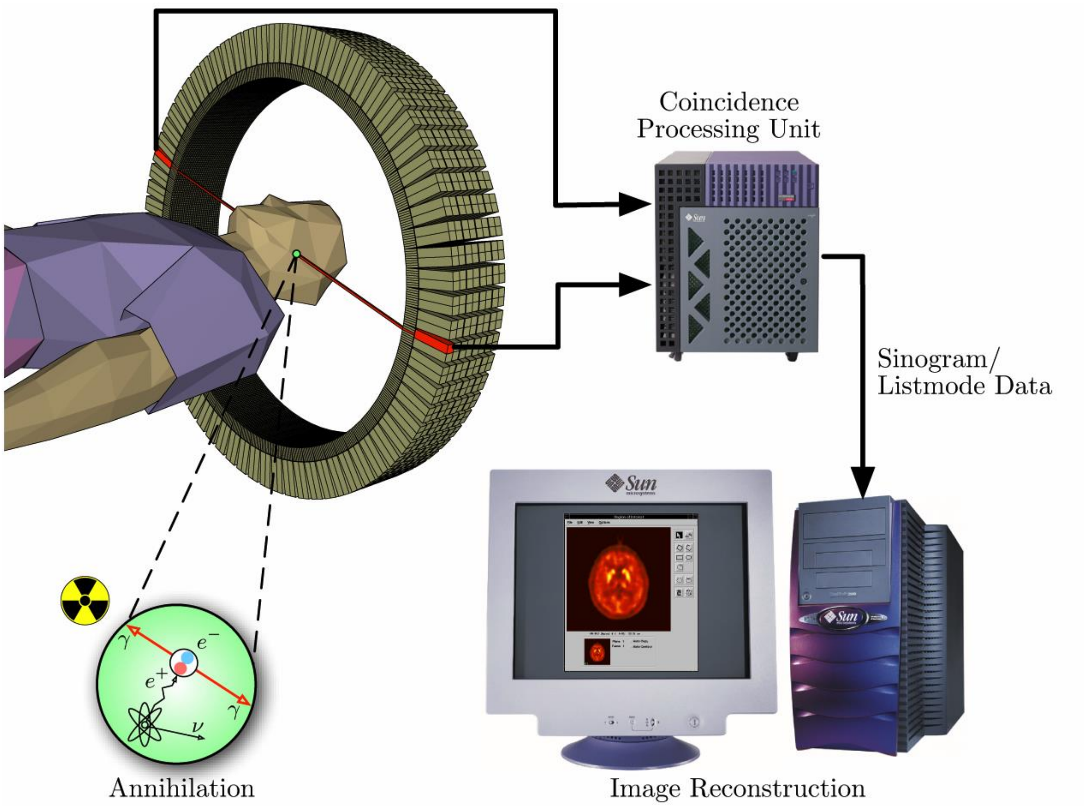
EFFICACY/QUALITY COST/SIZE/EFFICIENCY



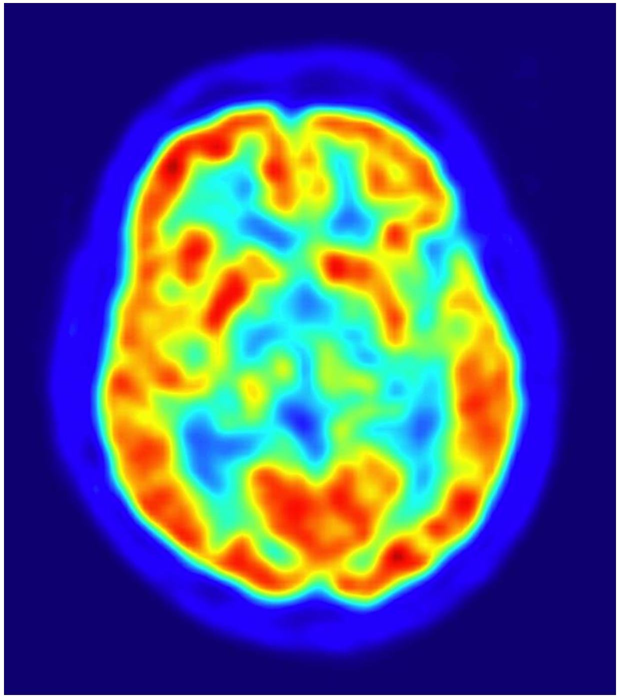
MedAustron: a facility which emerged from CERN study ‘PIMMS’.
A new study ‘NIMMS’ is underway.

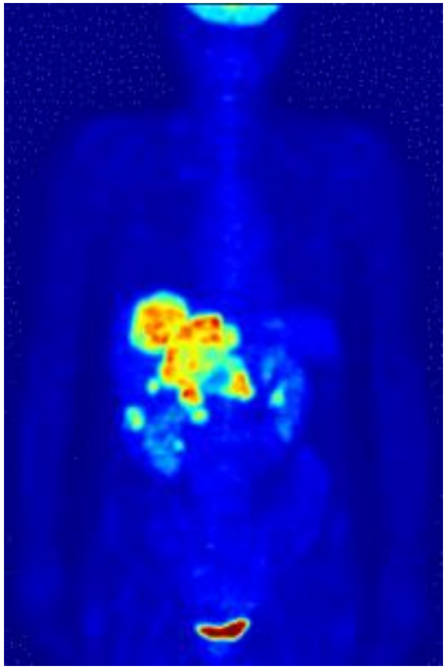
Radioisotope production

- 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

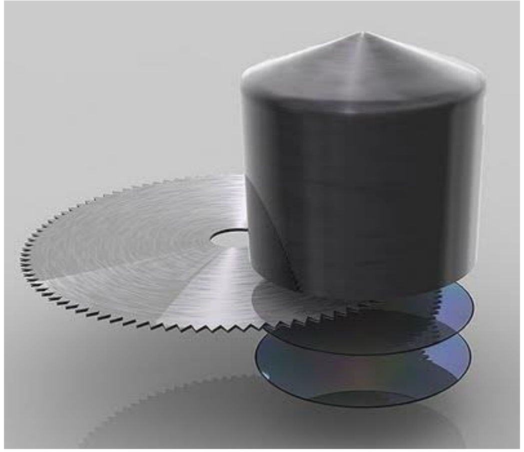
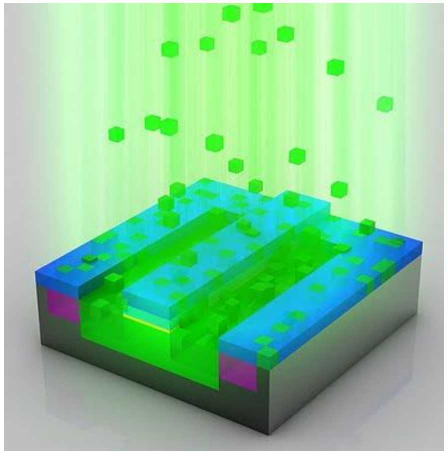
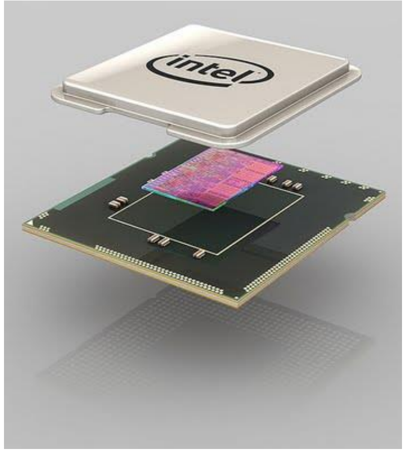
Isotopes used for PET, SPECT and Brachytherapy etc…

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**	

2. Industrial accelerators

Ion implantation

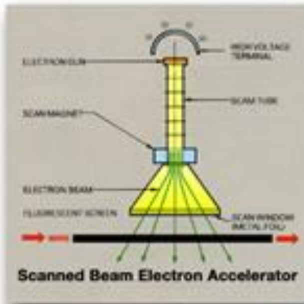
Images courtesy of Intel

- Electrostatic accelerators are used to deposit ions in semiconductors.

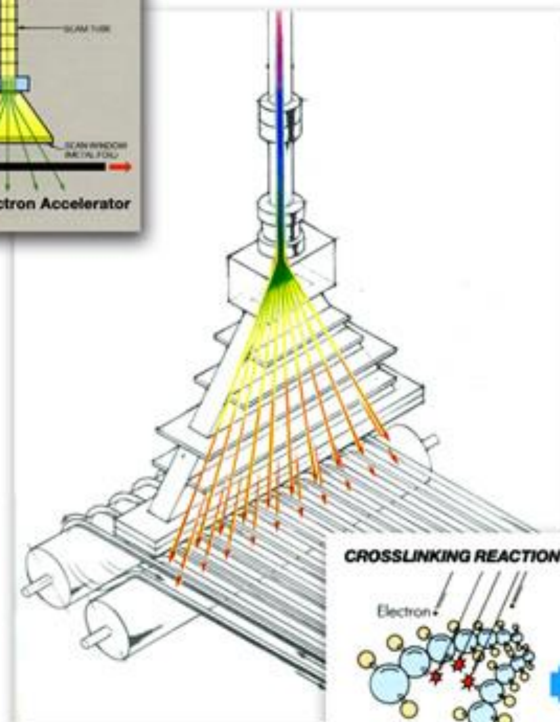
Electron beam processing

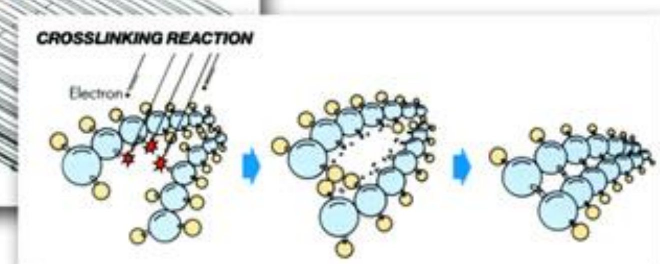
In the US, potential markets for industrial electron beams total $50 billion per year.

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



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.

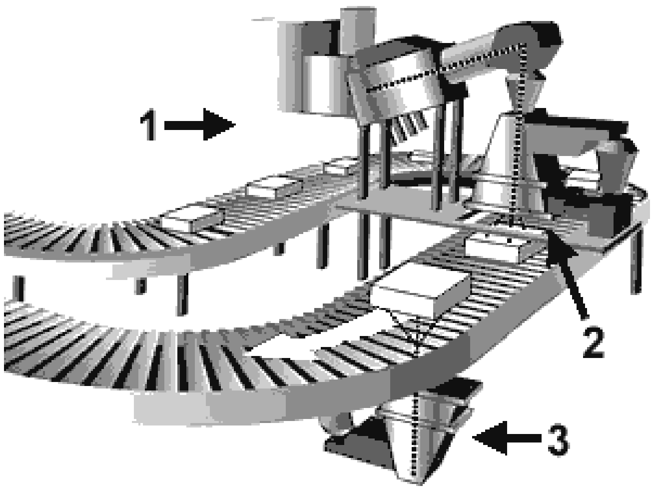
E-beam sterilisation works best on simple, low density products.

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

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

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

Food irradiation



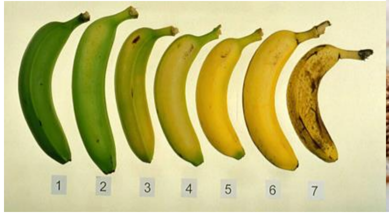
'Cold pasteurisation' or 'electronic pasteurisation'

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

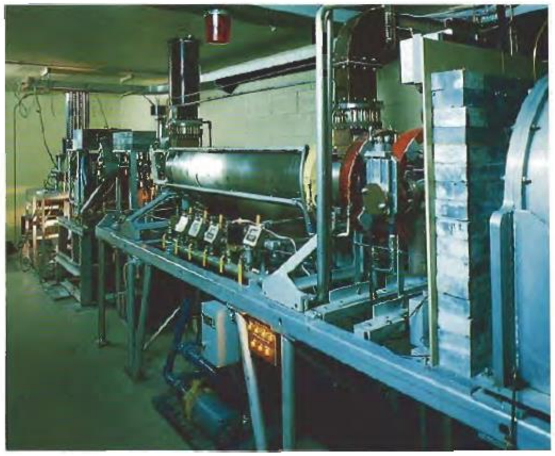
Foods authorised for irradiation in the EU:






Lower dose → Higher dose

Gemstone Irradiation



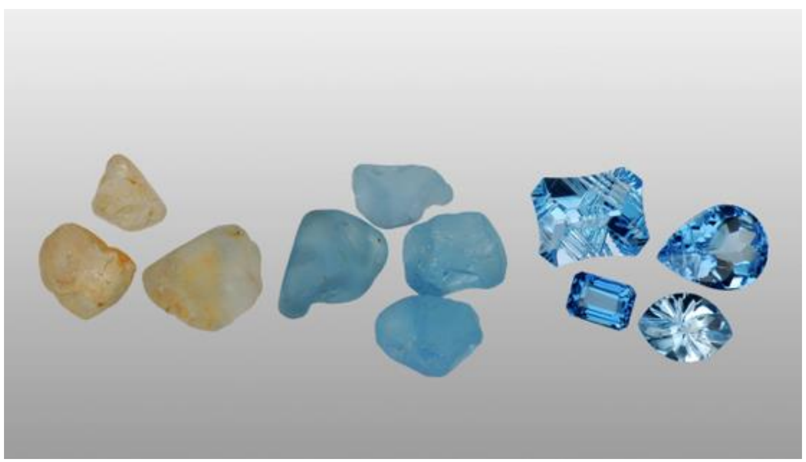


TABLE 2. Effects of irradiation treatment on various gem materials.[a]

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. Synchrotron Light Sources

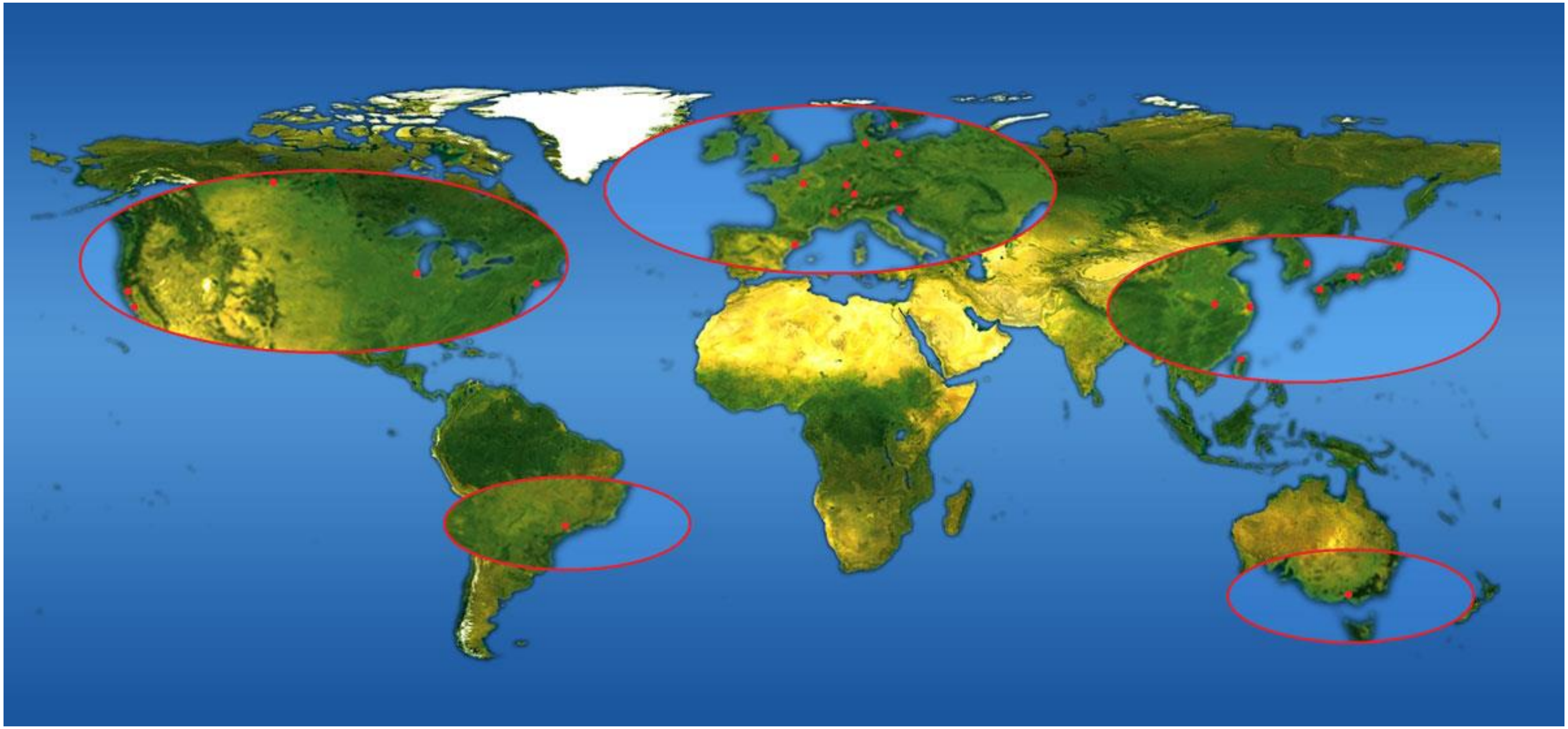
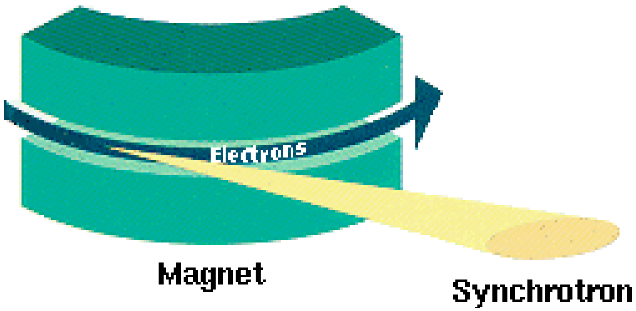
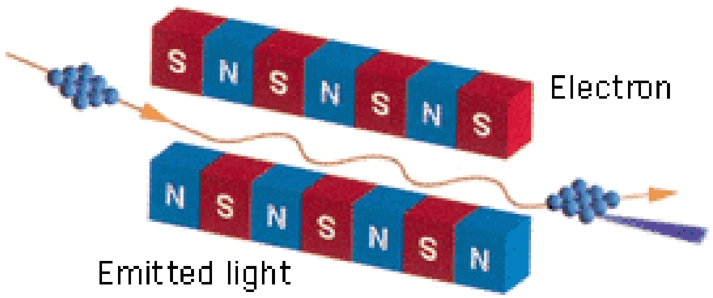
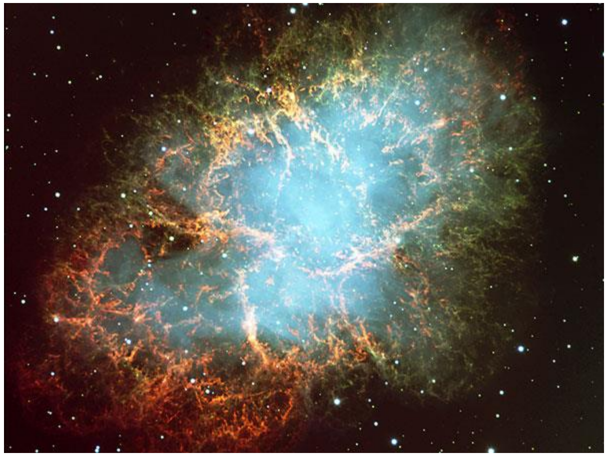


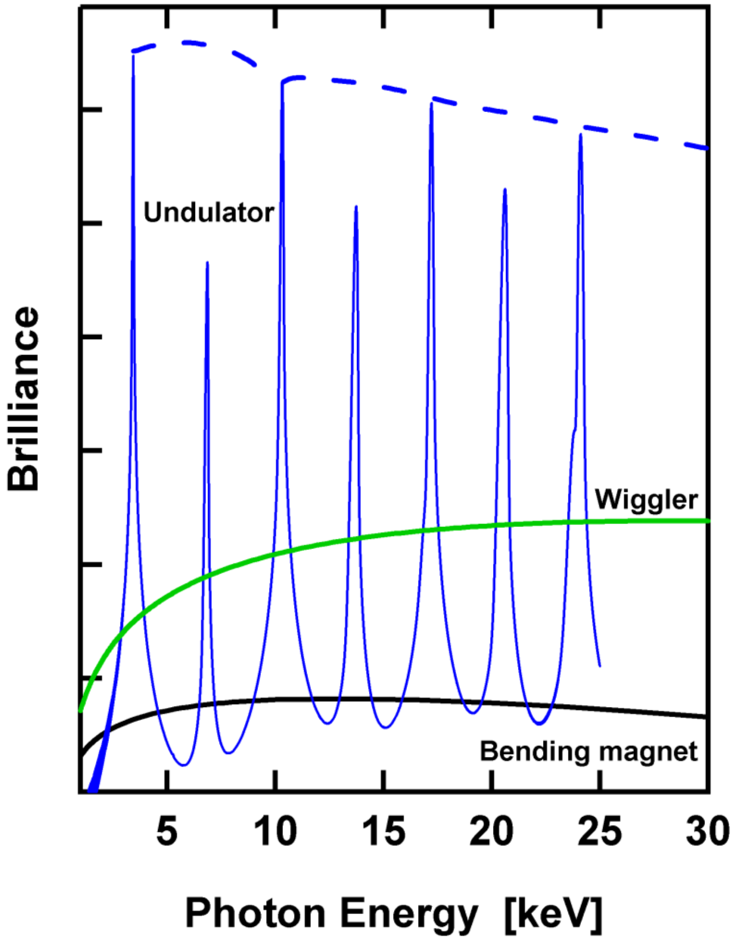
Image courtesy of ESRF

Synchrotron radiation is emitted by charged particles when accelerated radially







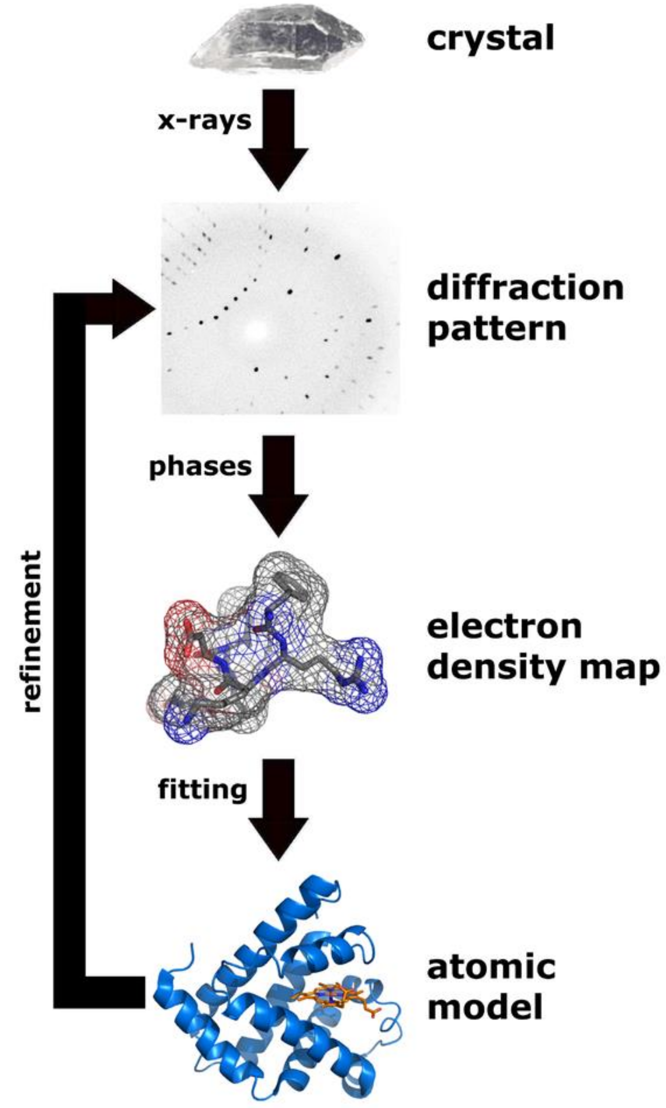


Produced in synchrotron radiation sources using bending magnets, undulators and wigglers

X-Ray crystallography

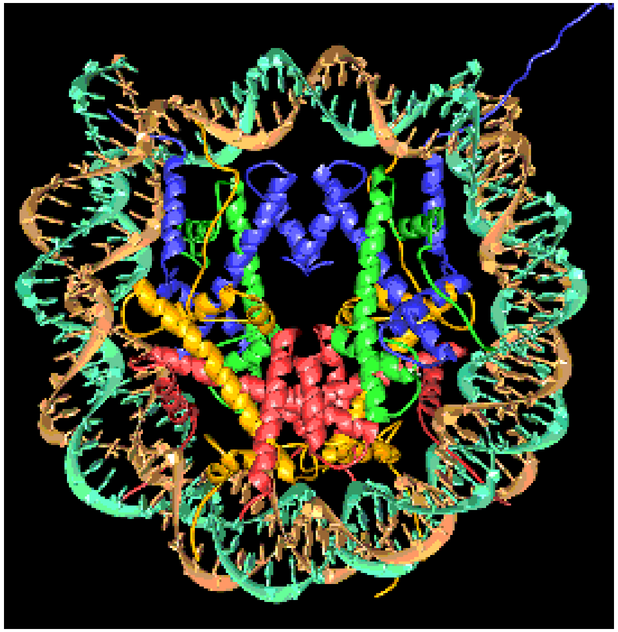
Protein crystallography is a standard technique at synchrotron light sources (Diamond light source has 5 beamlines devoted to it)

The hardest part is forming the crystal…

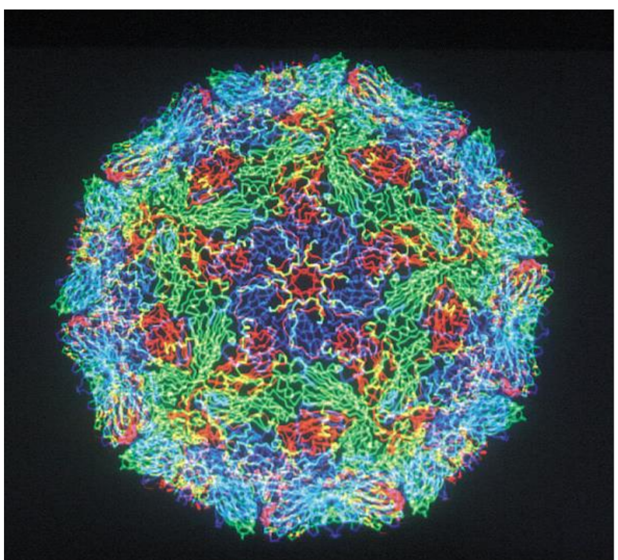


For some great overview videos of crystallography, see:
http://www.richannel.org/collections/2013/crystallography

Structural Biology

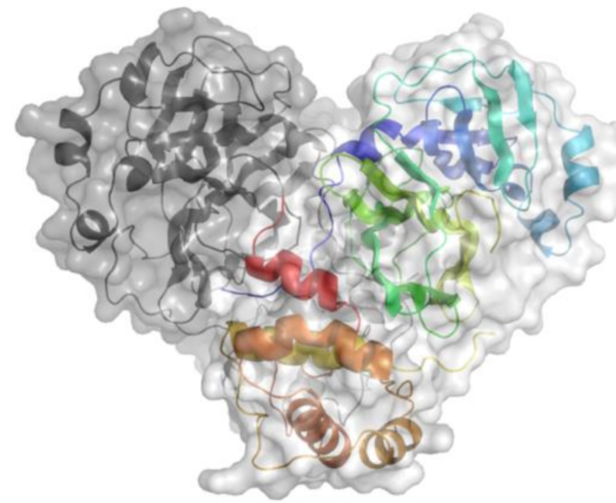


Reconstruction of the 3D structure of a nucleosome (DNA packaging) with a resolution of 0.2 nm



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

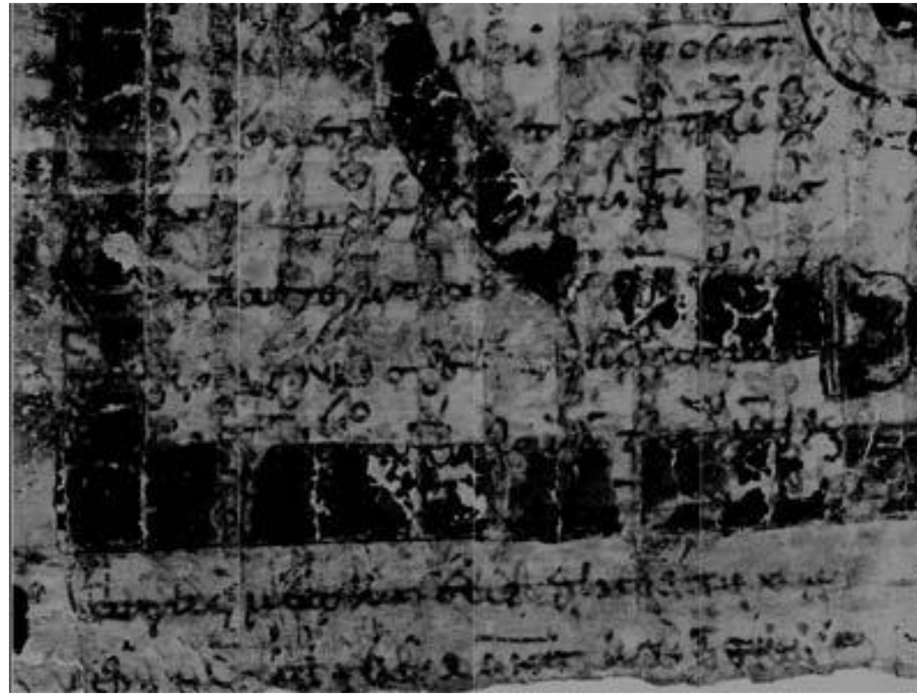


More info: https://cerncourier.com/a/synchrotrons-on-the-coronavirus-frontline/

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.



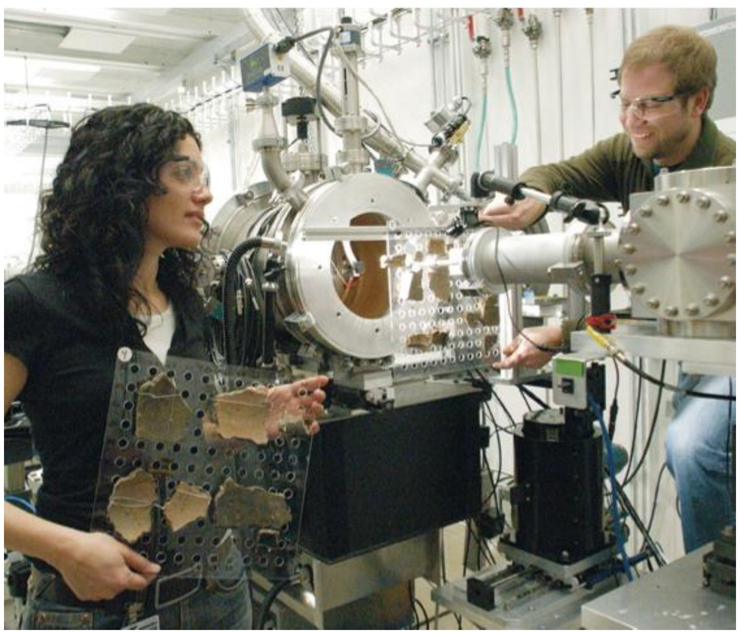


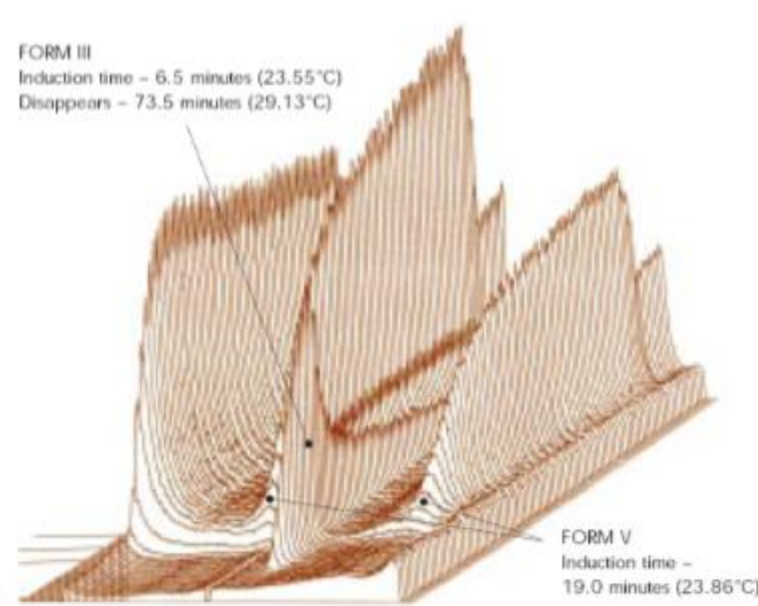
Image: Argonne National Laboratory

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

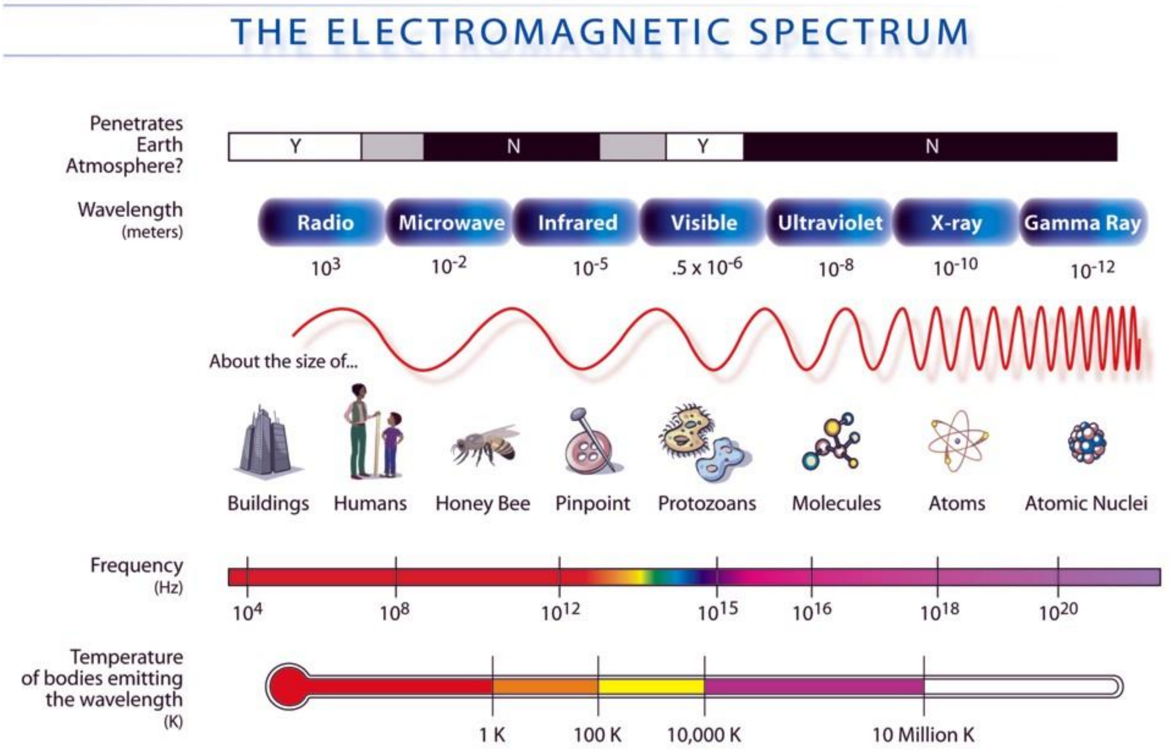
Crystal structure formation

Cadbury used X-rays from a particle accelerator to study how cocoa crystallises

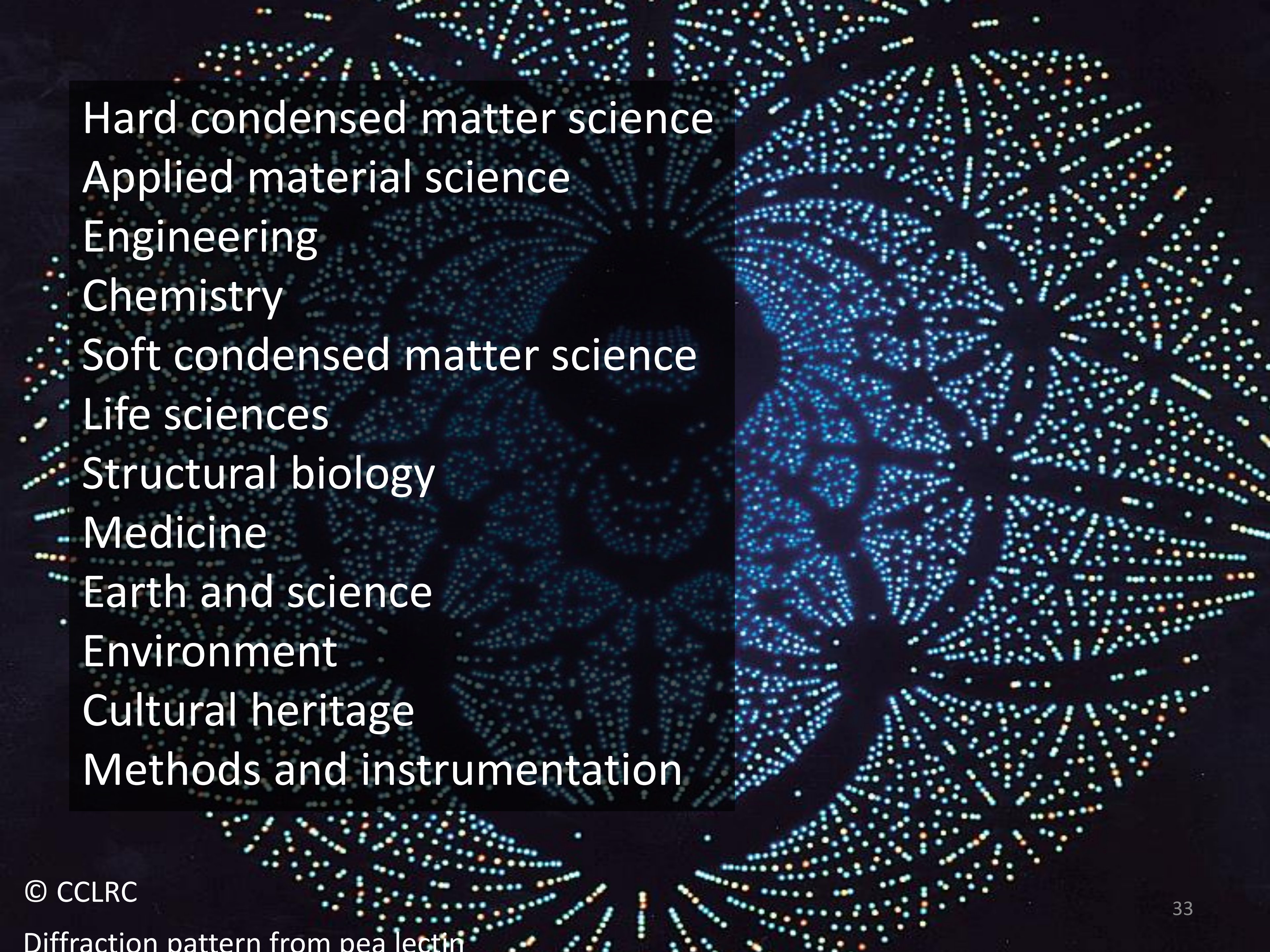
Of the six possible crystal forms, the fifth (form V) produces the best quality chocolate



- 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)



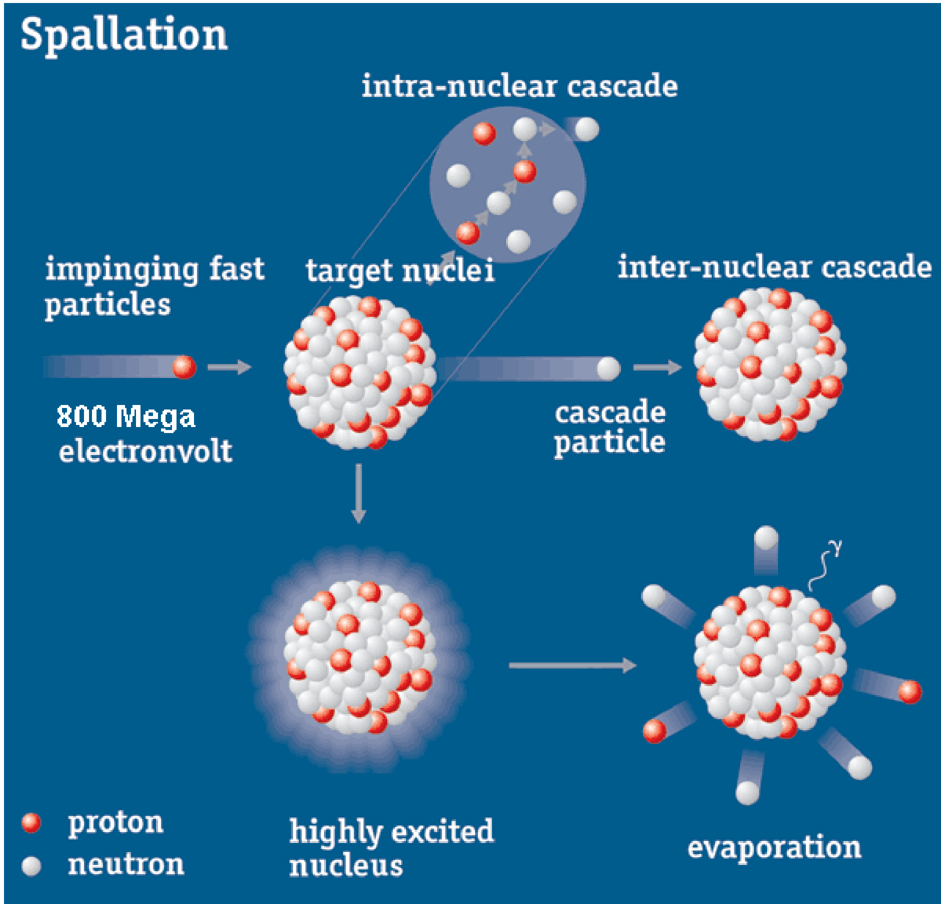
Hard condensed matter science
Applied material science
Engineering
Chemistry
Soft condensed matter science
Life sciences
Structural biology
Medicine
Earth and science
Environment
Cultural heritage
Methods and instrumentation

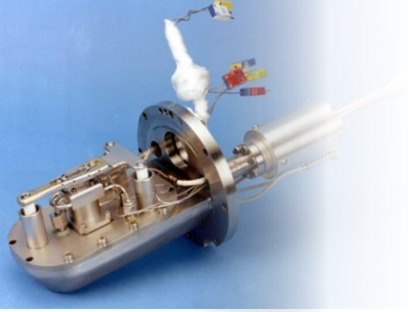
Diffraction pattern from pea lectin

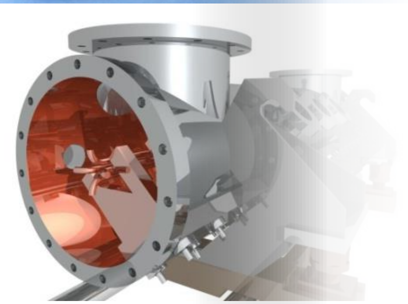
4. Neutron Spallation Sources

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

'Neutrons tell you where atoms ***are*** and what atoms ***do***'

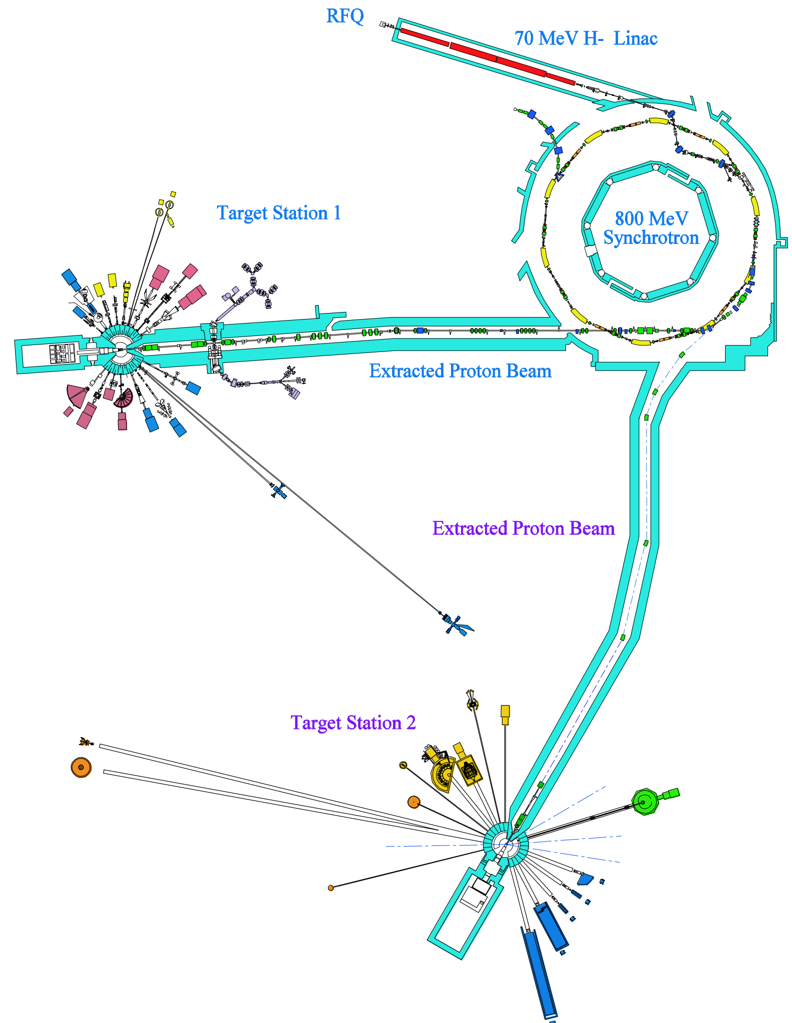






ISIS Accelerators and Targets

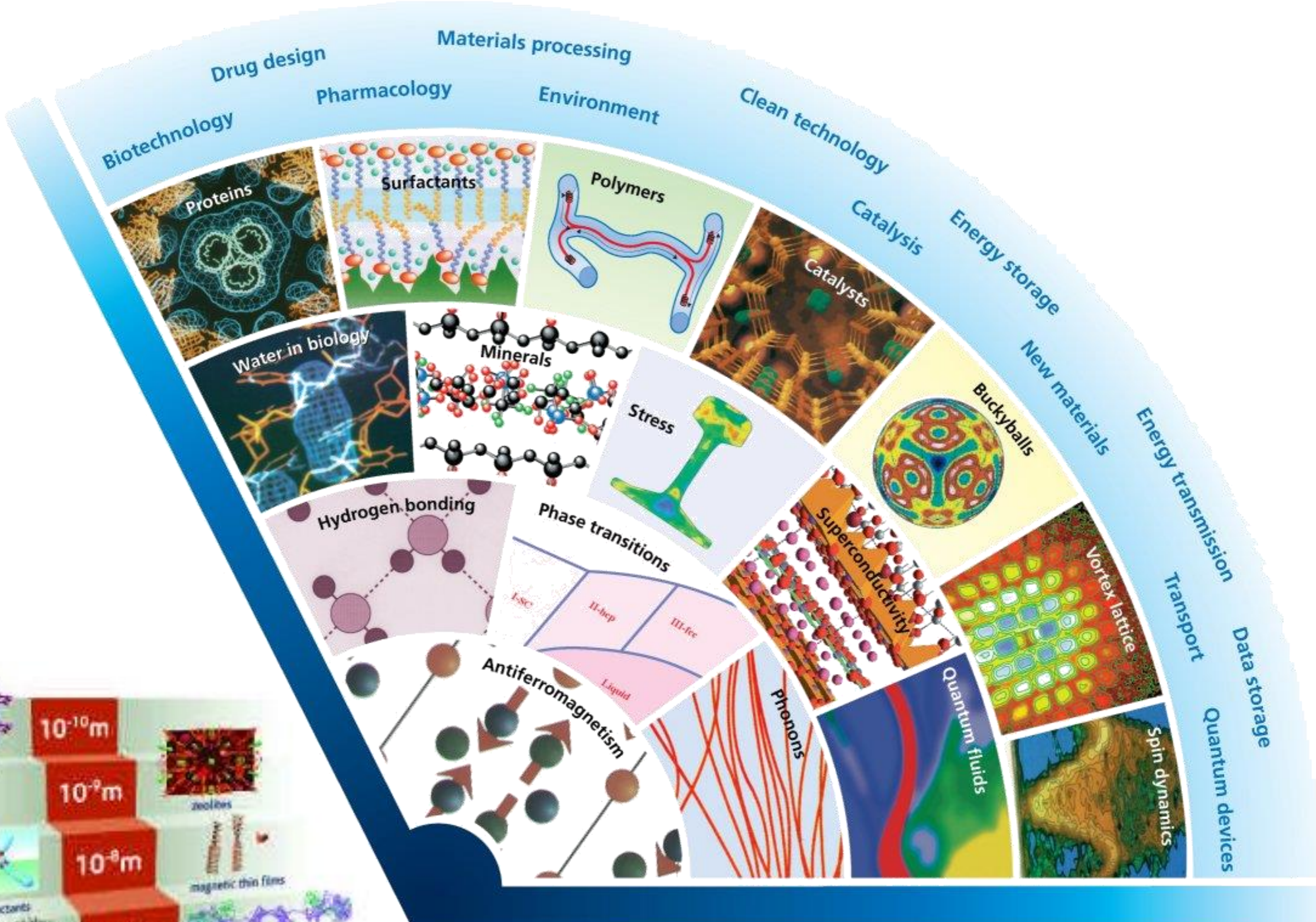
- H^- ion source (17 kV)
- 665 kV H^- RFQ
- 70 MeV H^- linac
- 800 MeV proton synchrotron
- Extracted proton beam lines
- Targets
- Moderators



Pulsed beam of 800 MeV (84% speed of light) protons at 50 Hz
Average beam current is 230 muA (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).

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



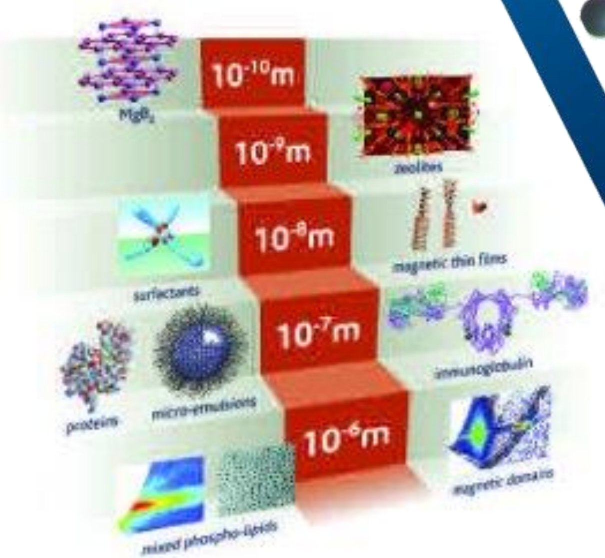
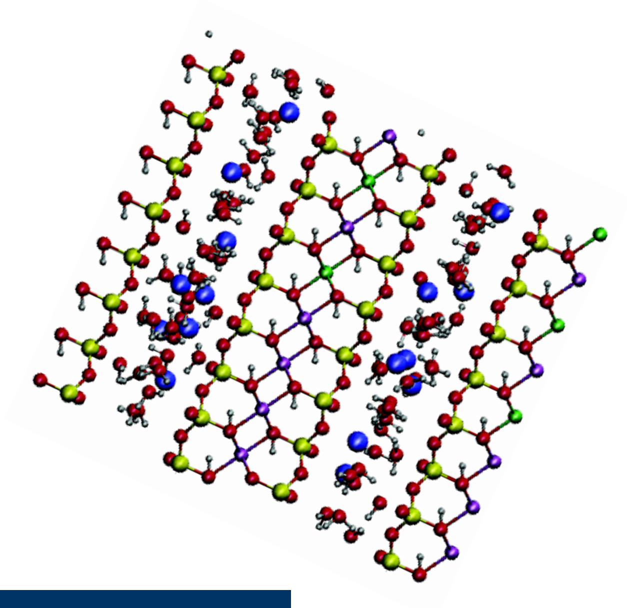


Image courtesy ISIS, STFC.

Unblocking oil pipes

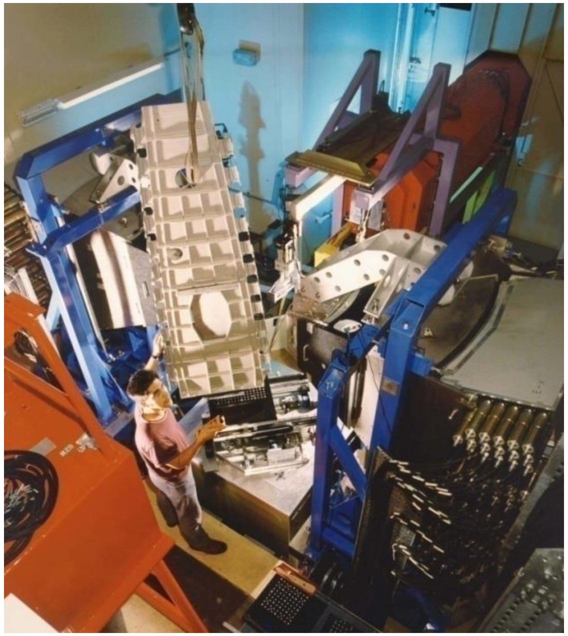
- **Asphaltenes** are a complex mixture of molecules that can sometimes **block oil pipes**
- Research to more easily **predict** and **prepare** for the formation of asphaltene deposits
- Result in **fewer blockages** and **big savings** for the oil industry.



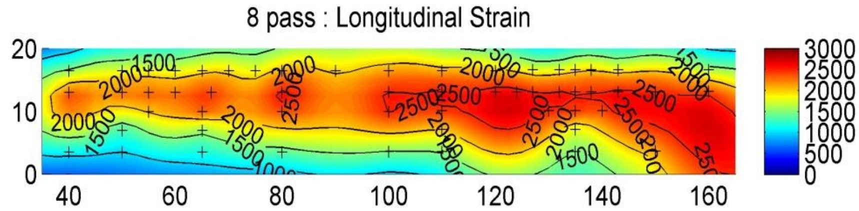
"ISIS allowed us to understand more clearly how asphaltenes aggregate, an important observation from a flow assurance point of view and should allow more efficient extraction of hydrocarbons in the future."
–Edo Boek, Schlumberger Cambridge Research, Senior Research Scientist

Schlumberger

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

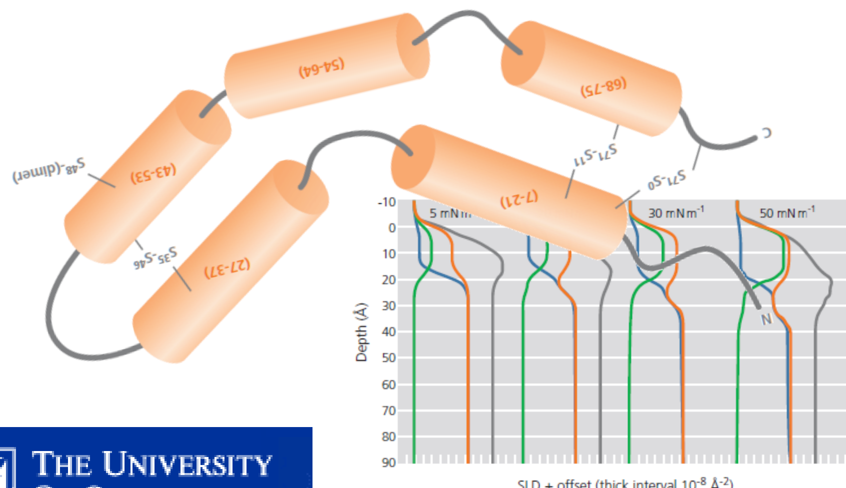


AIRBUS

"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



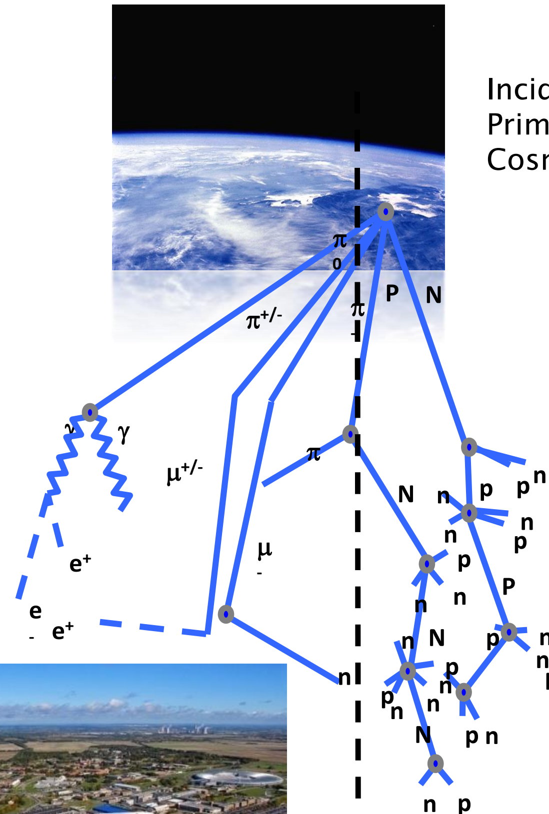
"ISIS is the premier place in the world to work with neutrons and liquid surfaces. In collaboration with the University of Queensland we were able to discover how proteins and phospholipids act together to enable lung function."

\- Dr Stephen Holt, ISIS neutron scientist

THE UNIVERSITY OF QUEENSLAND AUSTRALIA

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

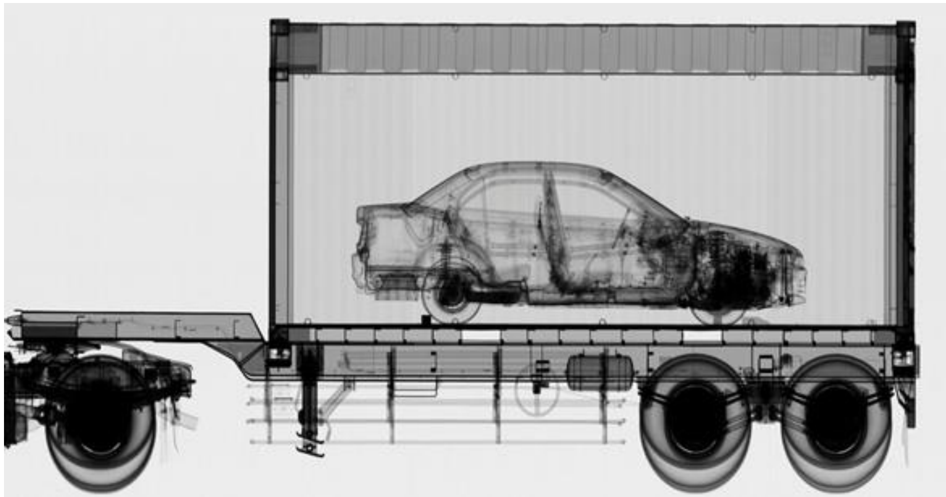


MBDA | BAE SYSTEMS | smiths | GOODRICH | uclan | LANCASTER UNIVERSITY | SURREY SPACE CENTRE | QinetiQ

"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

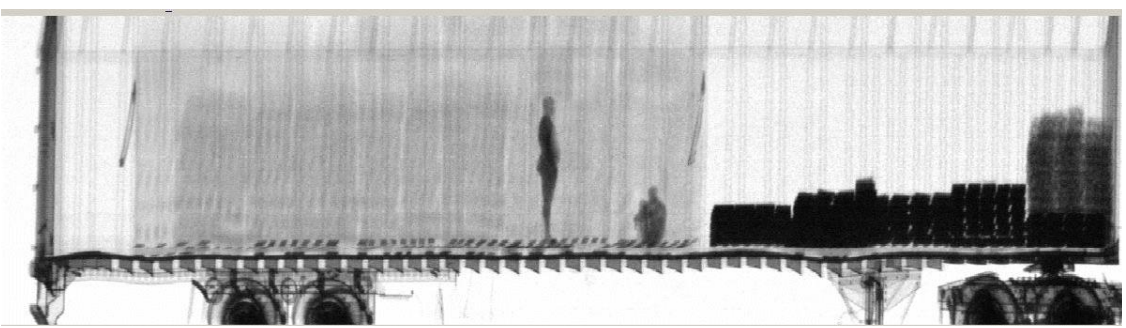


Image: dutch.euro

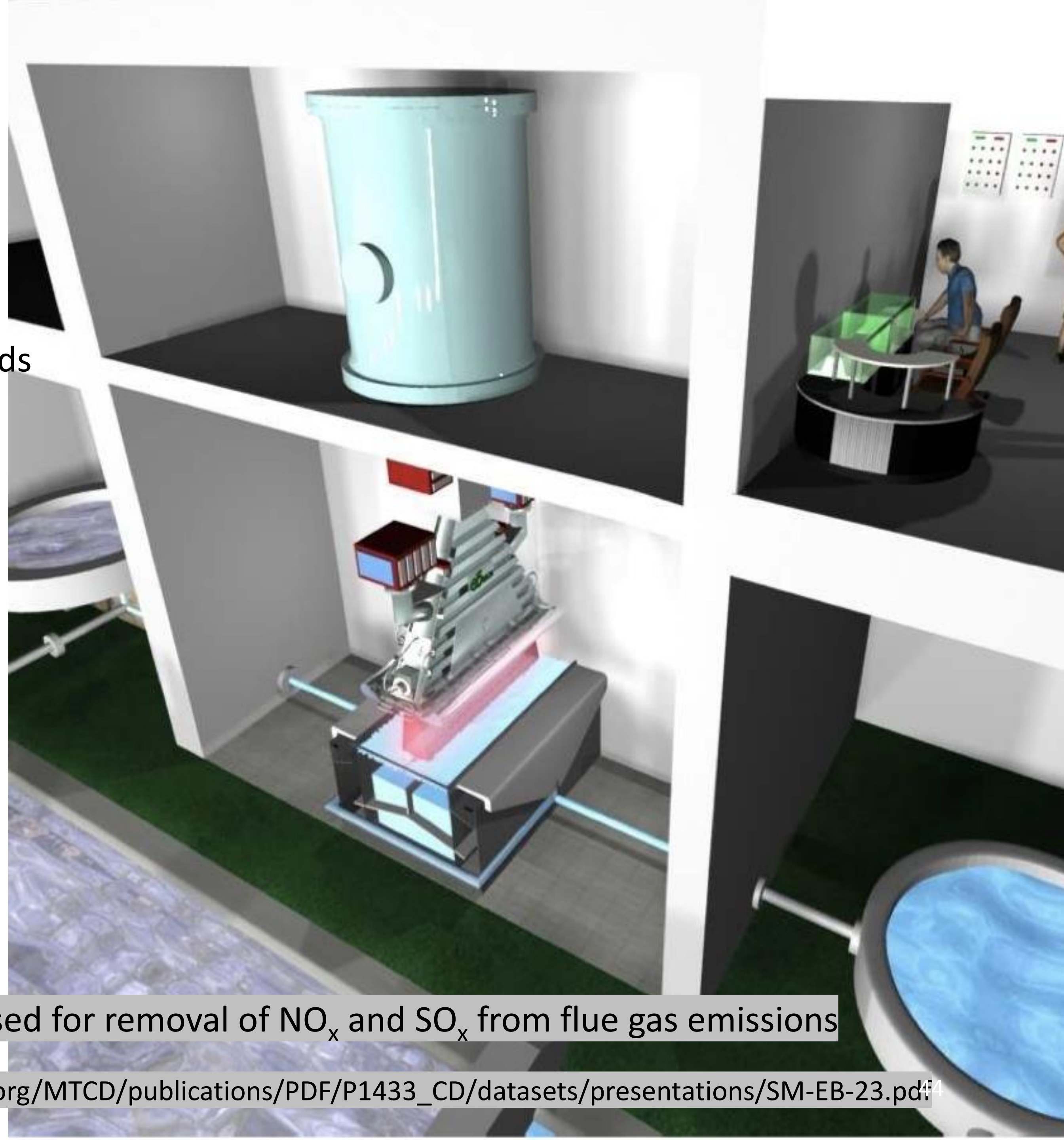
Wastewater Irradiation

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

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

Materials testing for fusion

Source: IFMIF.org

"deuterium-tritium nuclear fusion reactions will generate neutron fluxes in the order of 10^{18} $m^{-2}s^{-1}$ with an energy of 14.1 MeV that will collide with the first wall of the reactor vessel"

International Fusion Material Irradiation Facility (IFMIF)

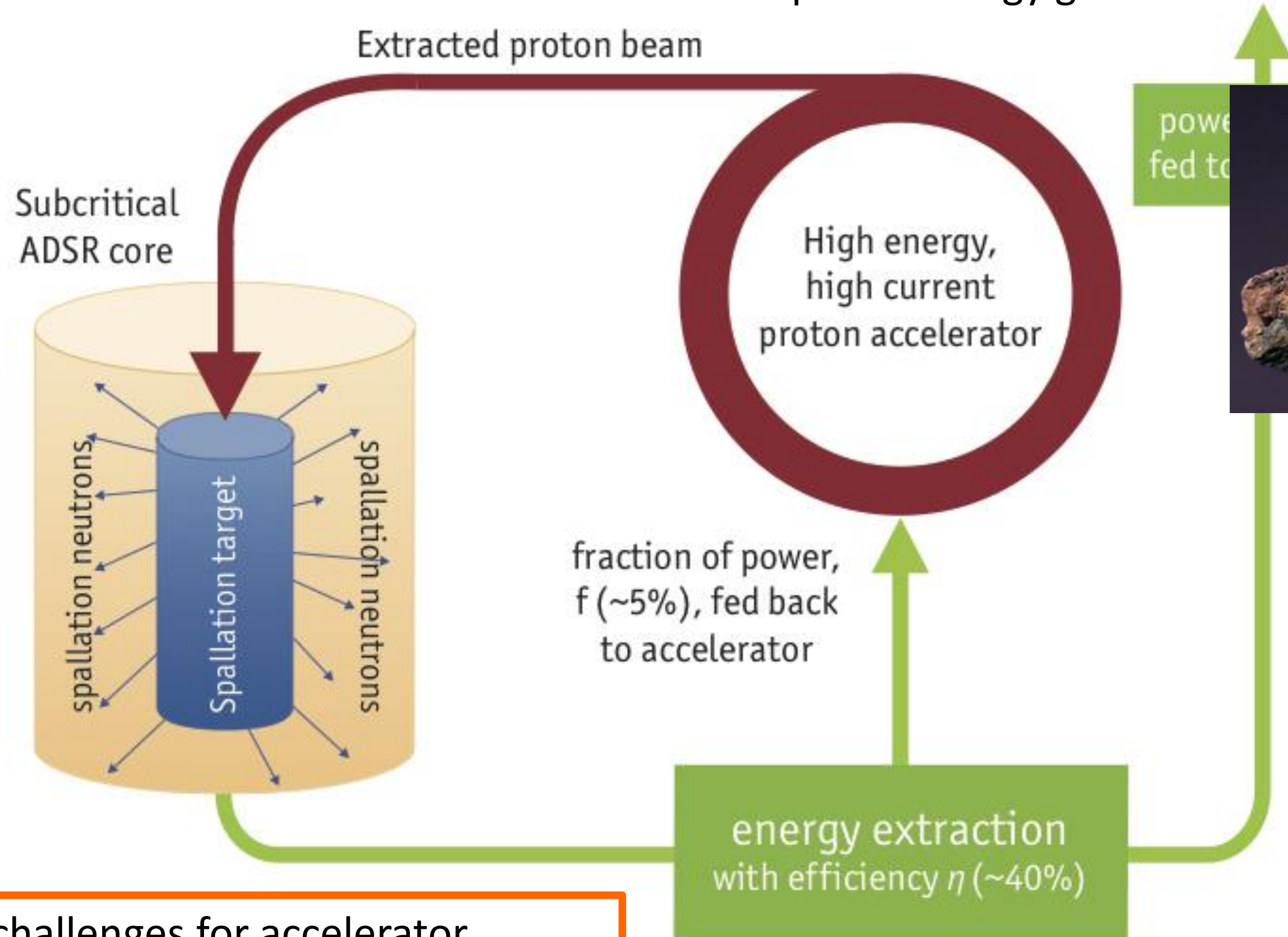
40 MeV
2 x 125mA linacs
CW deuterons, 5MW each
Beams will overlap onto a liquid Li jet
To create conditions similar to in a fusion reactor

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

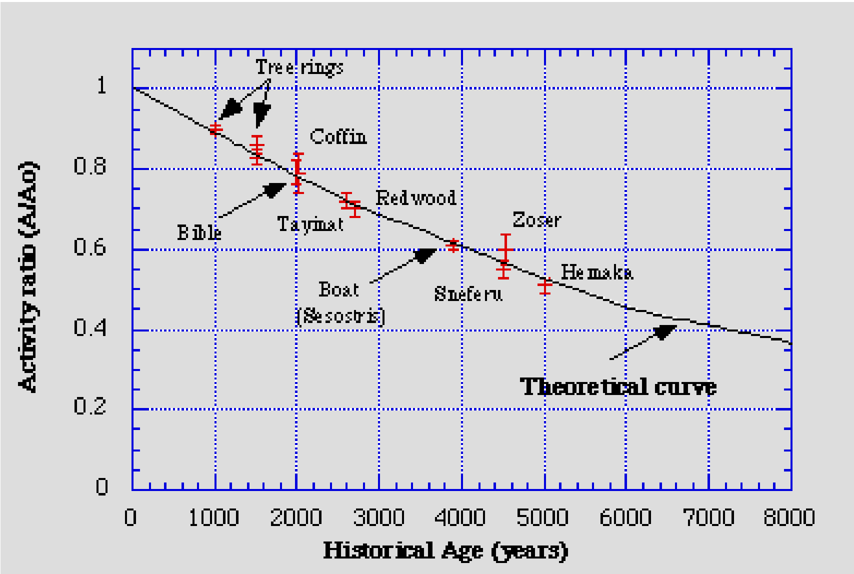


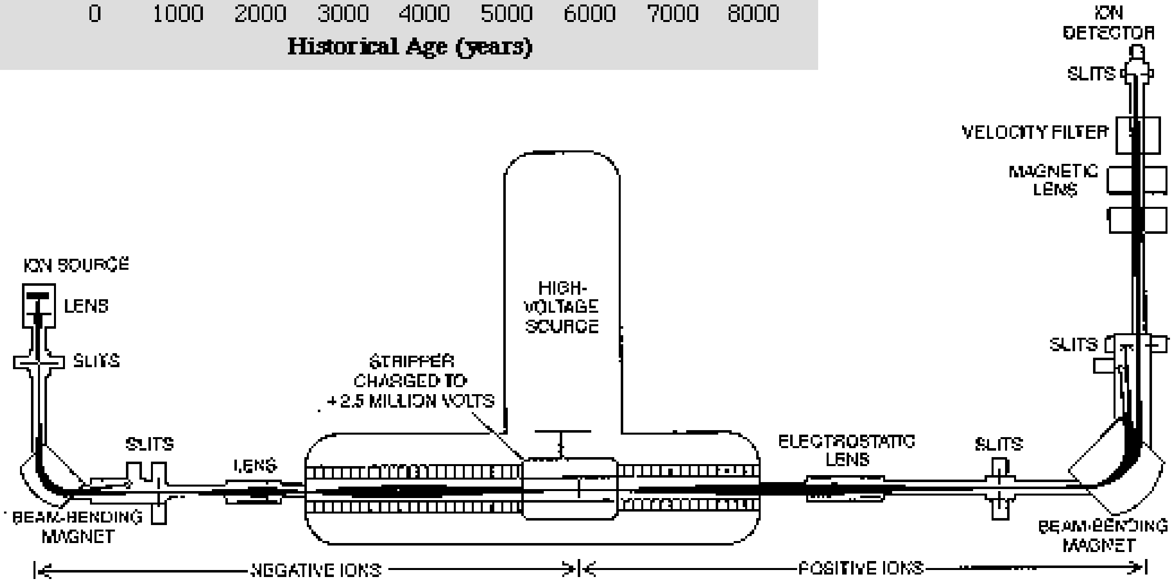
Thorium

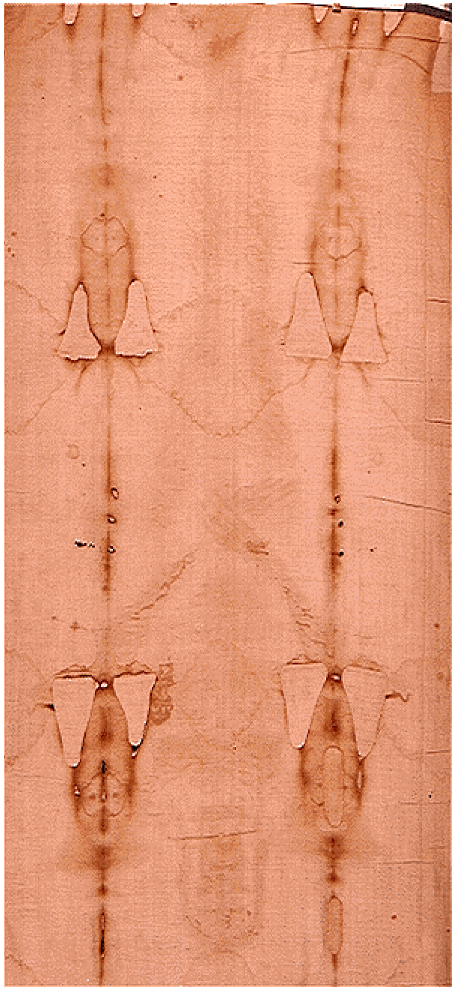
Major challenges for accelerator technology in terms of beam power (>10MW) and reliability

6. Historical and cultural applications

Radiocarbon Dating



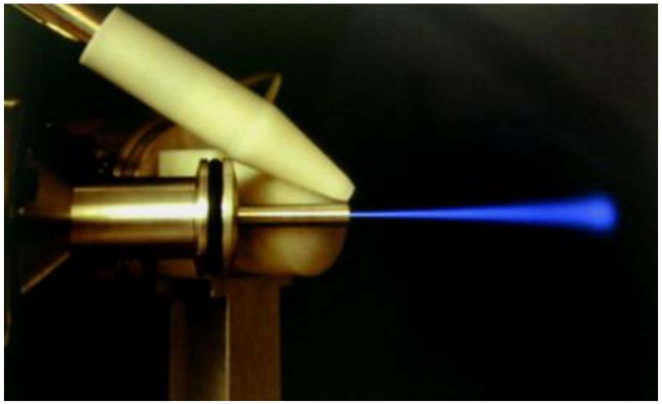




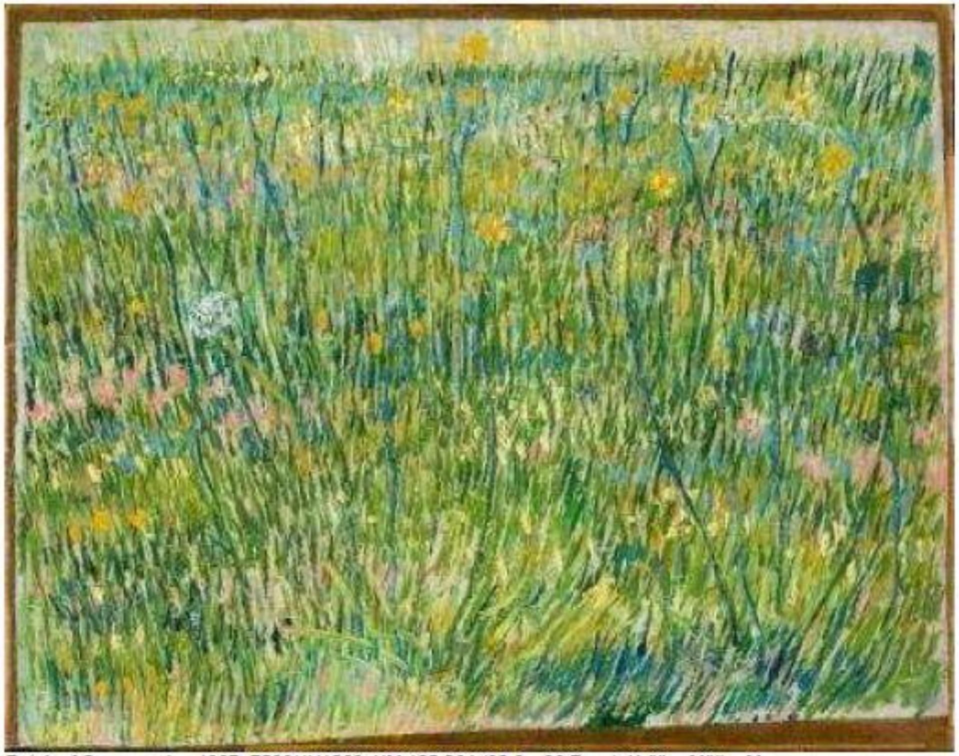
For more accuracy, isolate C-14 from other isotopes
"AMS" = Accelerator Mass Spectrometry

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



IBA techniques: to study art

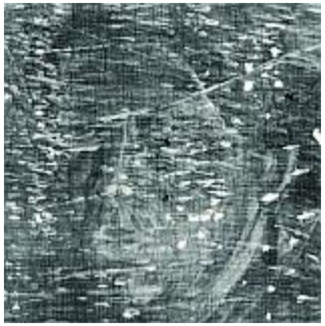


Patch of Grass, spring 1887, F583/JH1263, KM 105.264 (30,8 x 39,7 cm), Kröller-Müller Museum (Photo: Rik Klein Gotink)

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

http://www.javno.com/en-bestseller/van-gogh-first-victim-of-particle-bombarding_185316

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

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Atomic boffins spot fake wines

0 0 0 0 Email

Bottles are zapped with beams of charged ions generated by a particle accelerator

Bottles are zapped with beams of charged ions generated by a particle accelerator

By Roger Highfield, Science Editor
7:25PM BST 03 Sep 2008

A rare wine merchant has joined forces with nuclear scientists to develop a 21st-century tool for unmasking counterfeit vintage wines.

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