

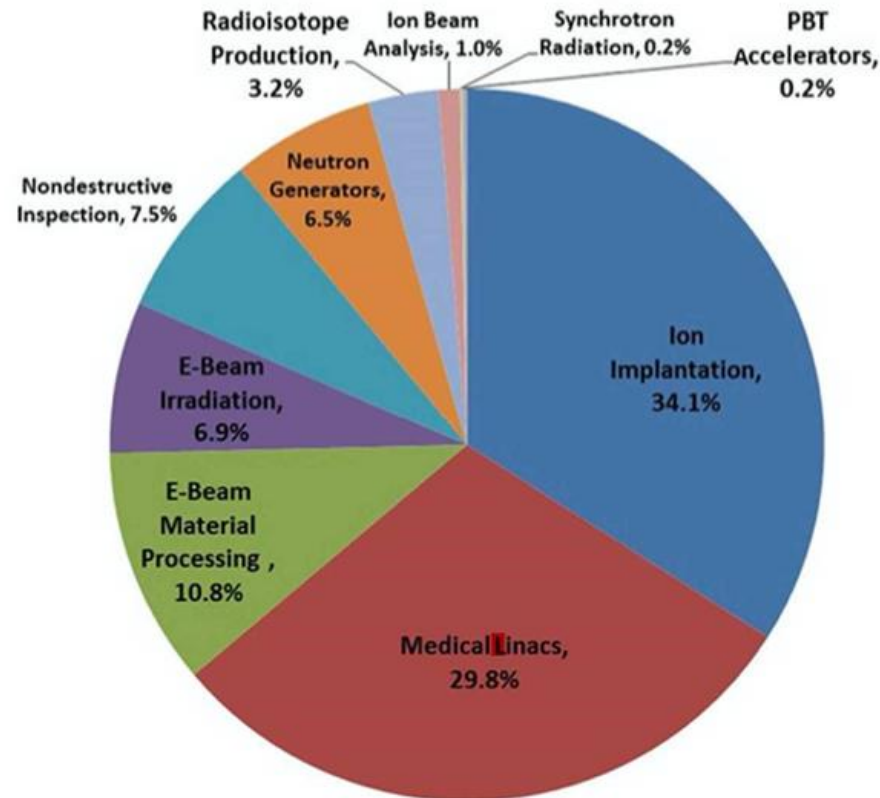


# Applications of Accelerators

CERN Introductory Accelerator School  
Kaunas, Lithuania, 2022

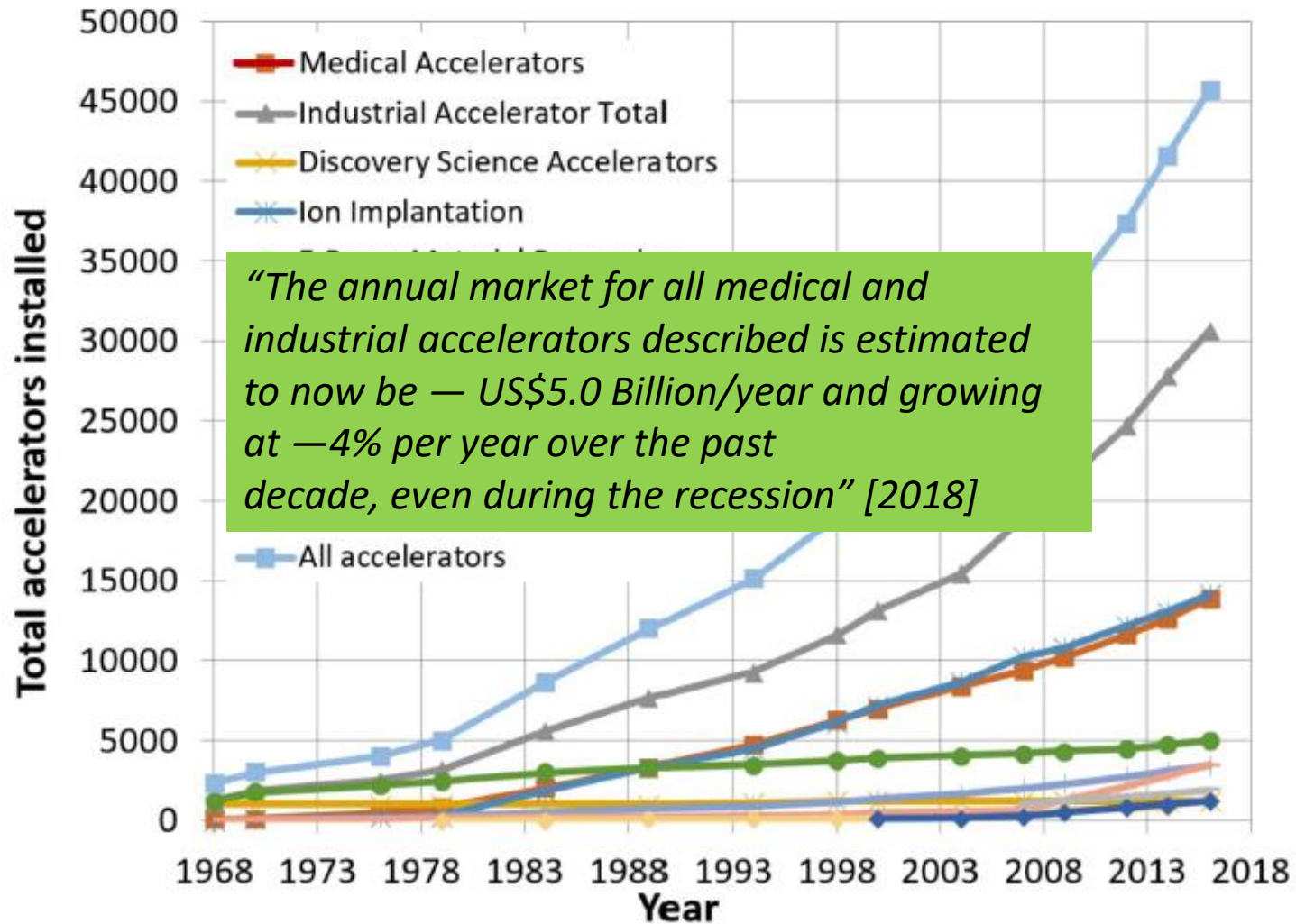
Dr. Suzie Sheehy  
@suziesheehy  
[suzie.sheehy@unimelb.edu.au](mailto:suzie.sheehy@unimelb.edu.au)

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



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

## Accelerators Installed Worldwide



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

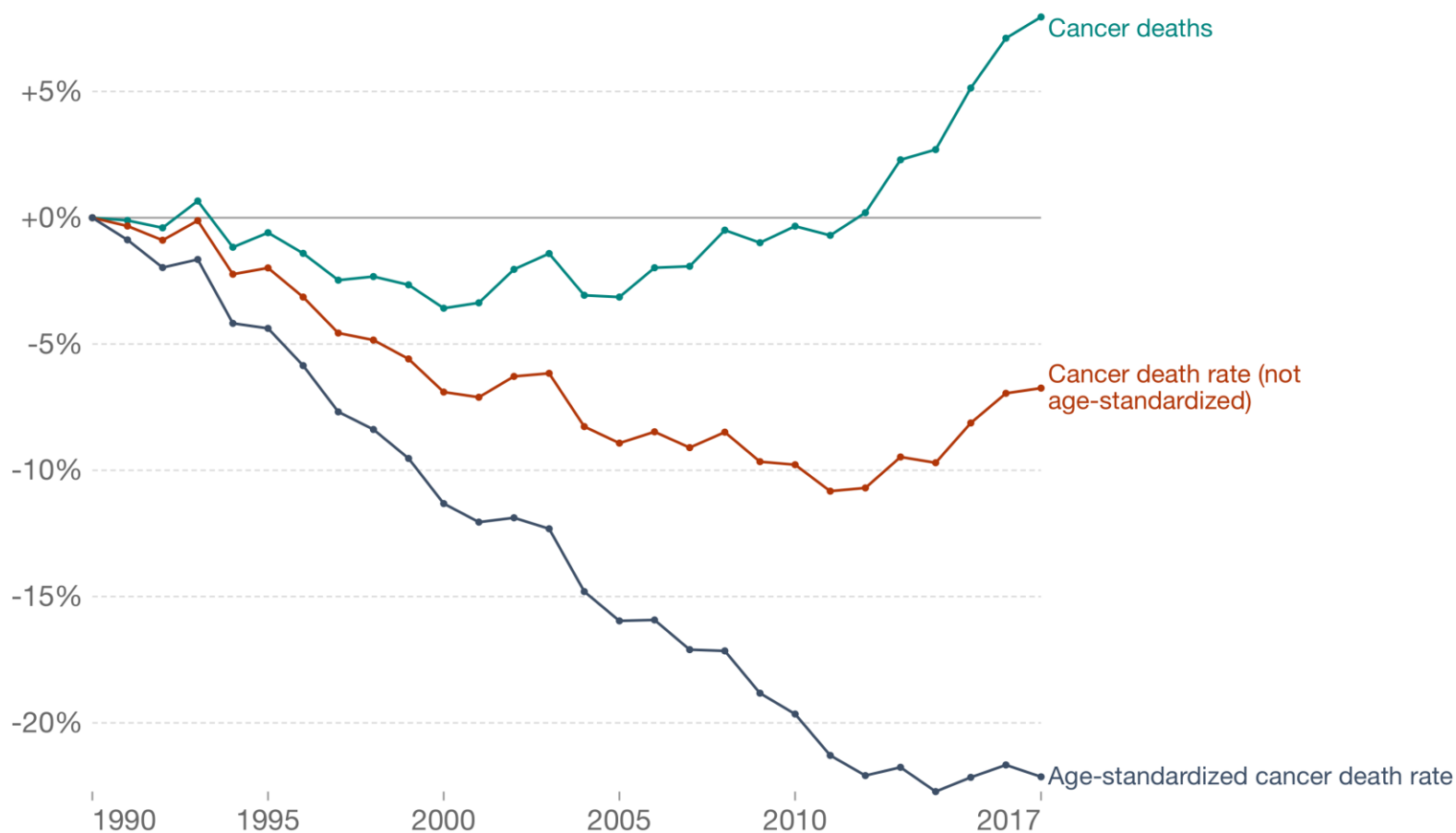
# Outline

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

# 1. Medical Applications

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

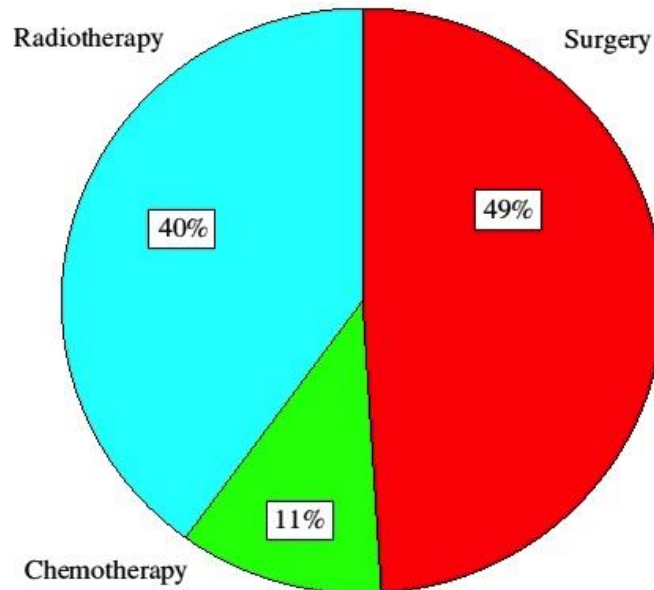
This chart compares cancer deaths, the cancer death rate, and the age-standardized death rate.



Source: Global Burden of Disease [IHME]

OurWorldInData.org/cancer • CC BY

## Patients cured by the major cancer treatment modalities



Chemotherapy  
- alone  
- with surgery  
- with radiotherapy

Reference  
Cancer Services Collaborative 2002  
[www.nhs.uk/npat](http://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

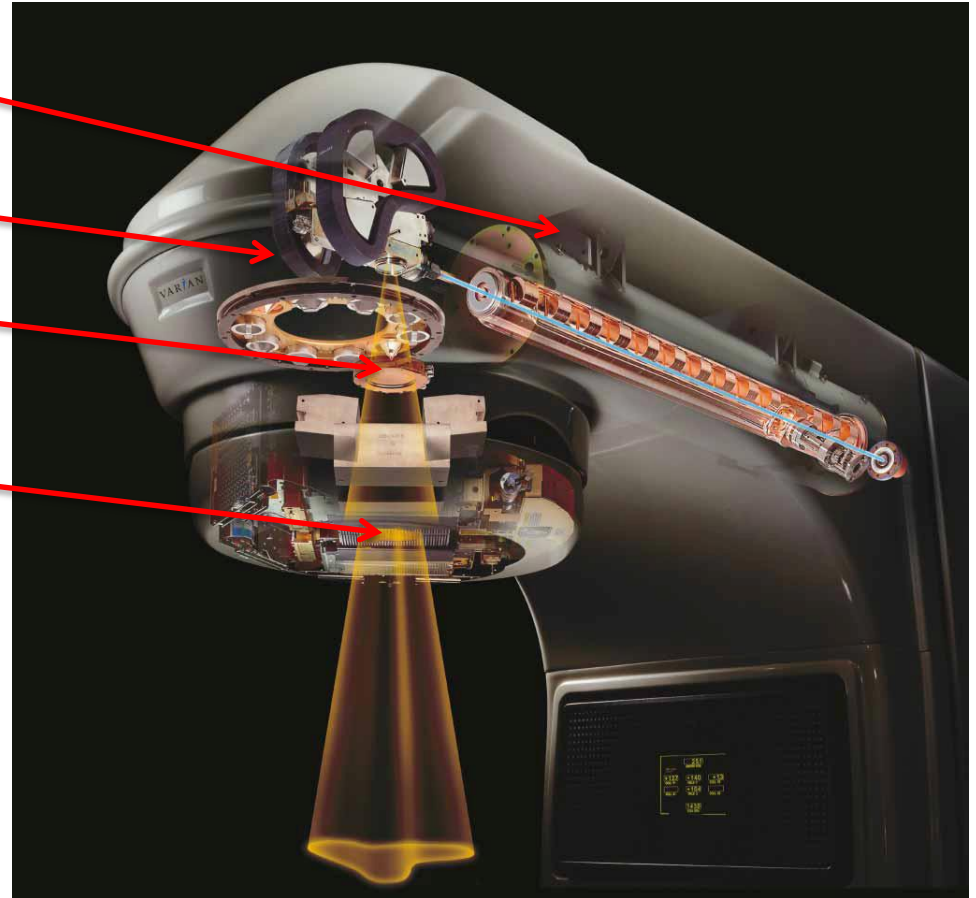
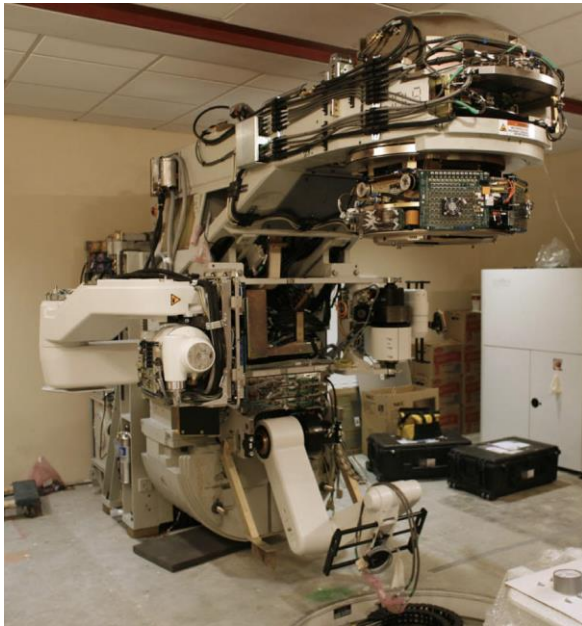
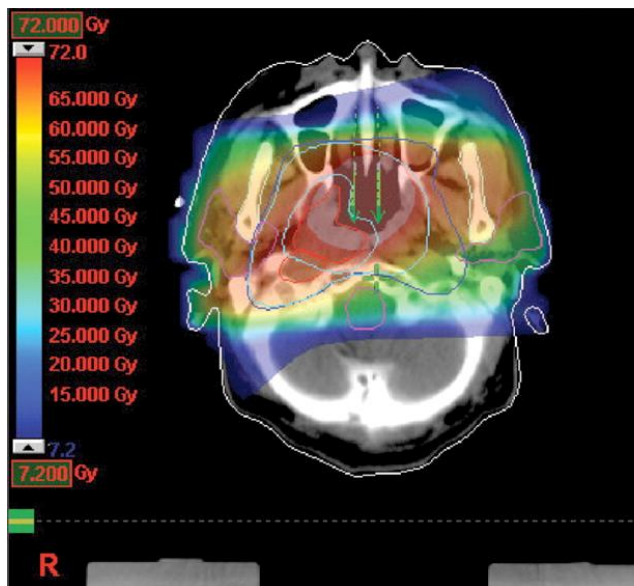
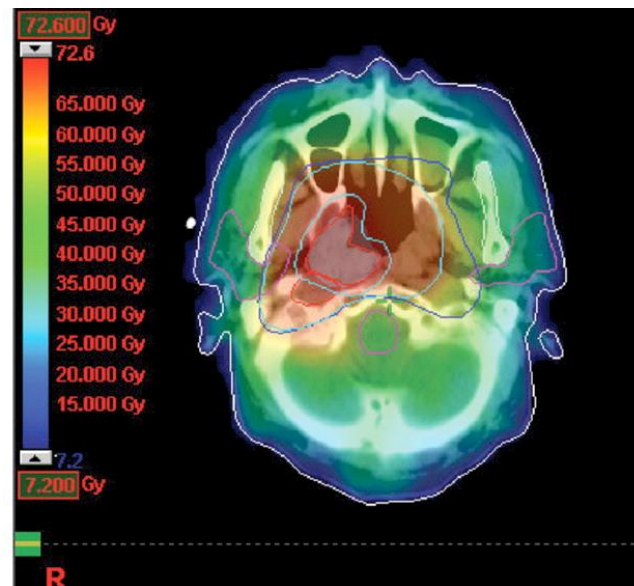


Image: copyright Varian medical systems

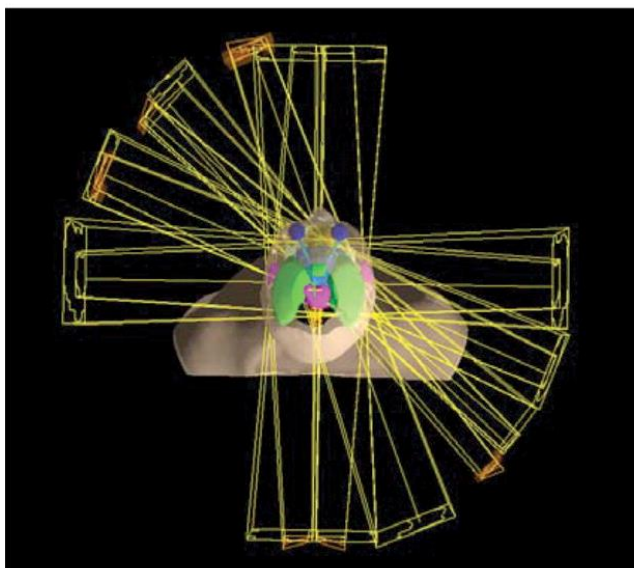




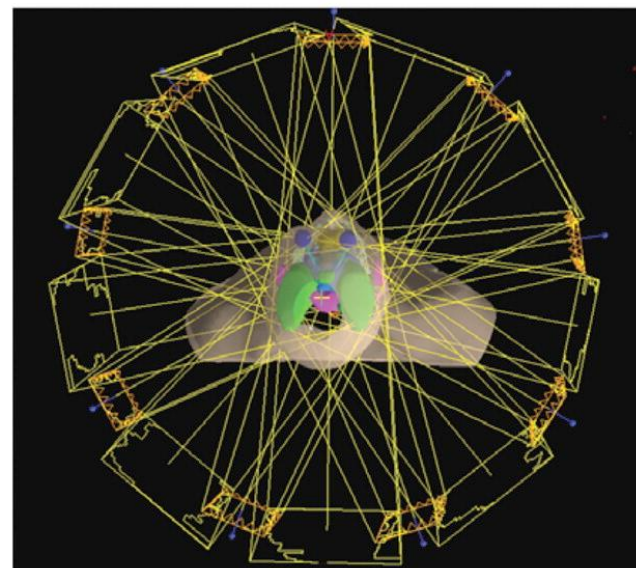
(a)



(b)



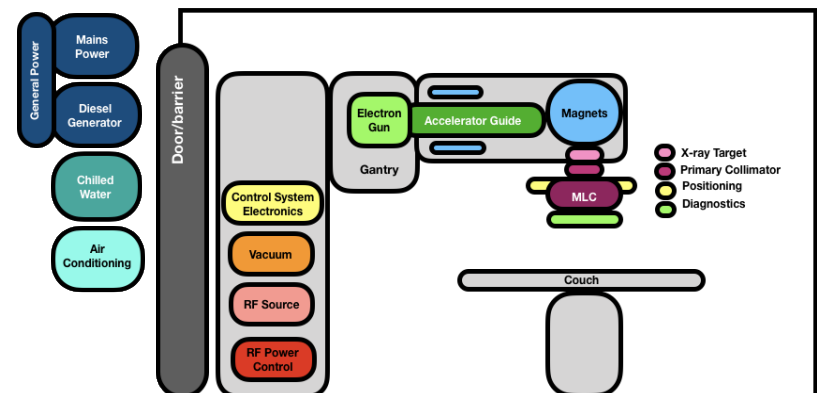
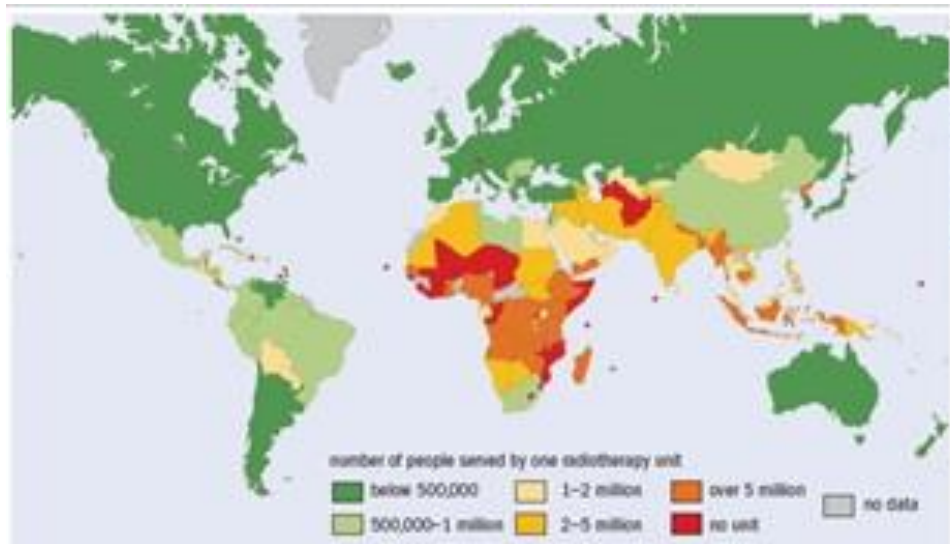
(c)



(d)

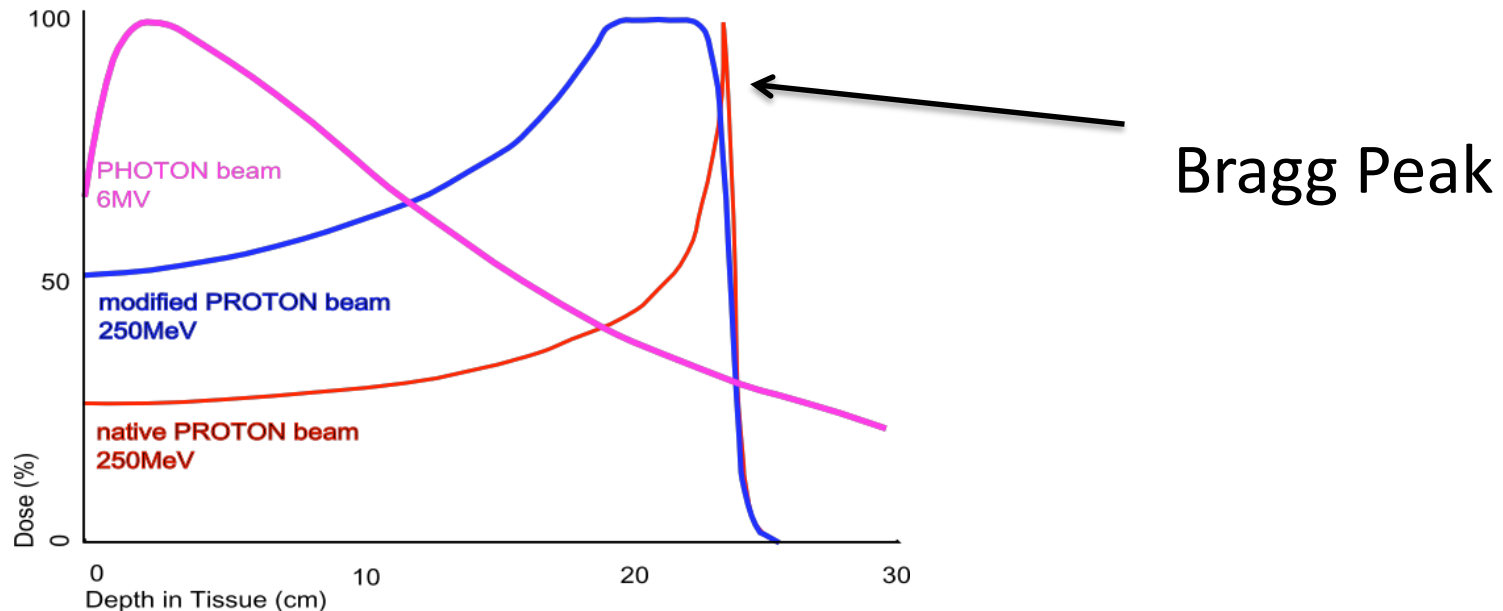
# A Global Challenge in Healthcare:

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



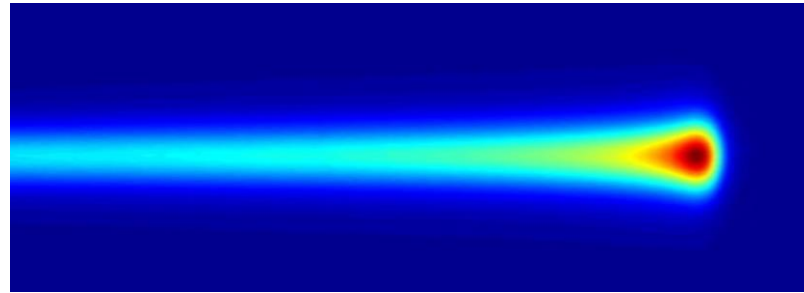
STELLA Collaboration Formed to Address this Issue

# Charged Particle Therapy



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

# Energy loss in matter (+tissue)



$$-\left\langle \frac{dE}{dx} \right\rangle = \frac{4\pi}{m_e c^2} \cdot \frac{n z^2}{\beta^2} \left( \frac{e^2}{4\pi\epsilon_0} \right)^2 \cdot \left[ \ln \left( \frac{2m_e c^2 \beta^2}{I \cdot (1 - \beta^2)} \right) - \beta^2 \right]$$

$$\beta = v / c$$

$v$  velocity of the particle

$E$  energy of the particle

$x$  distance travelled by the particle

$c$  speed of light

$z$  particle charge

$e$  charge of the electron

$m_e$  rest mass of the electron

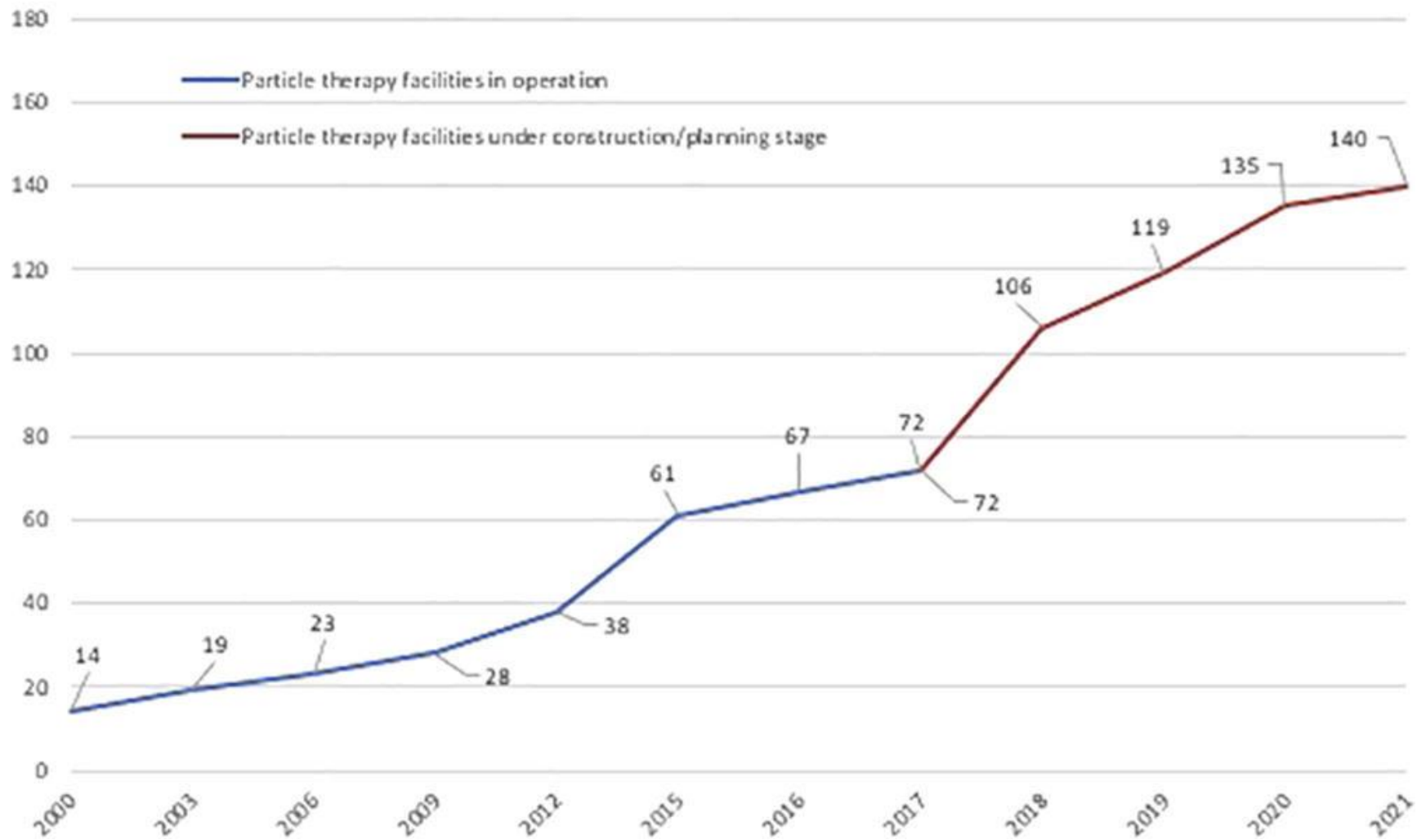
$n$  electron density of the target

$I$  mean excitation potential of the target

$\epsilon_0$  vacuum permittivity

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

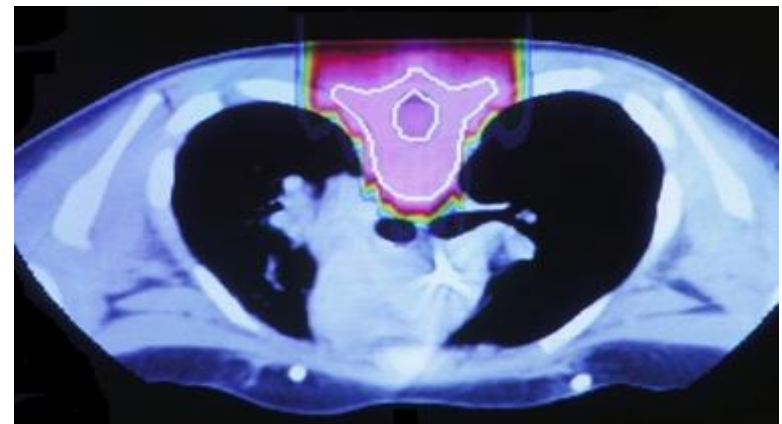
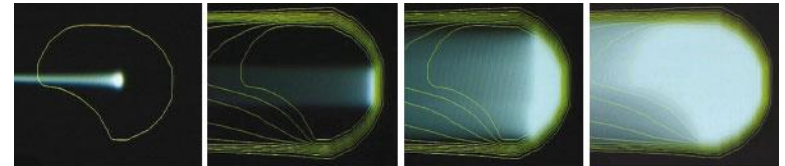
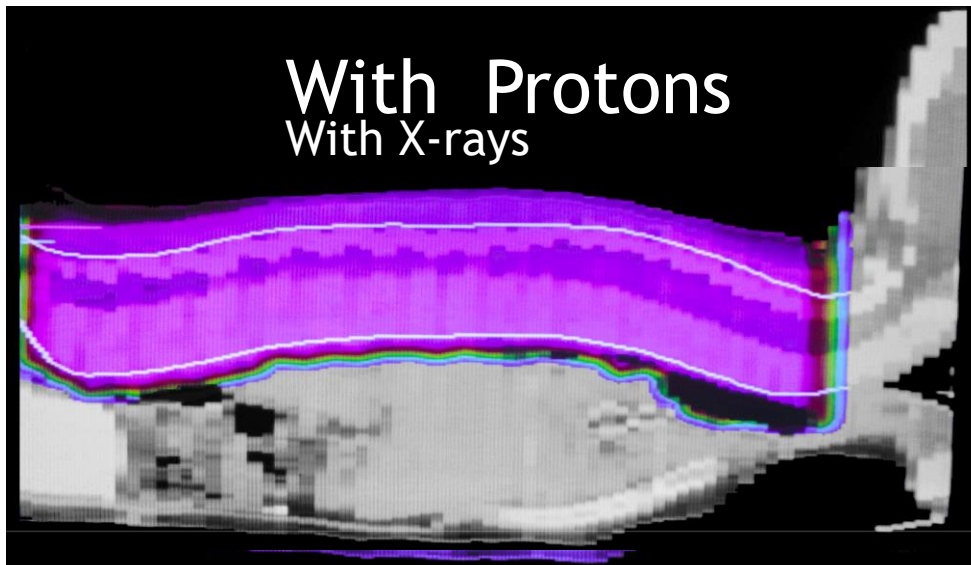
## Particle therapy facilities in operation





# 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:

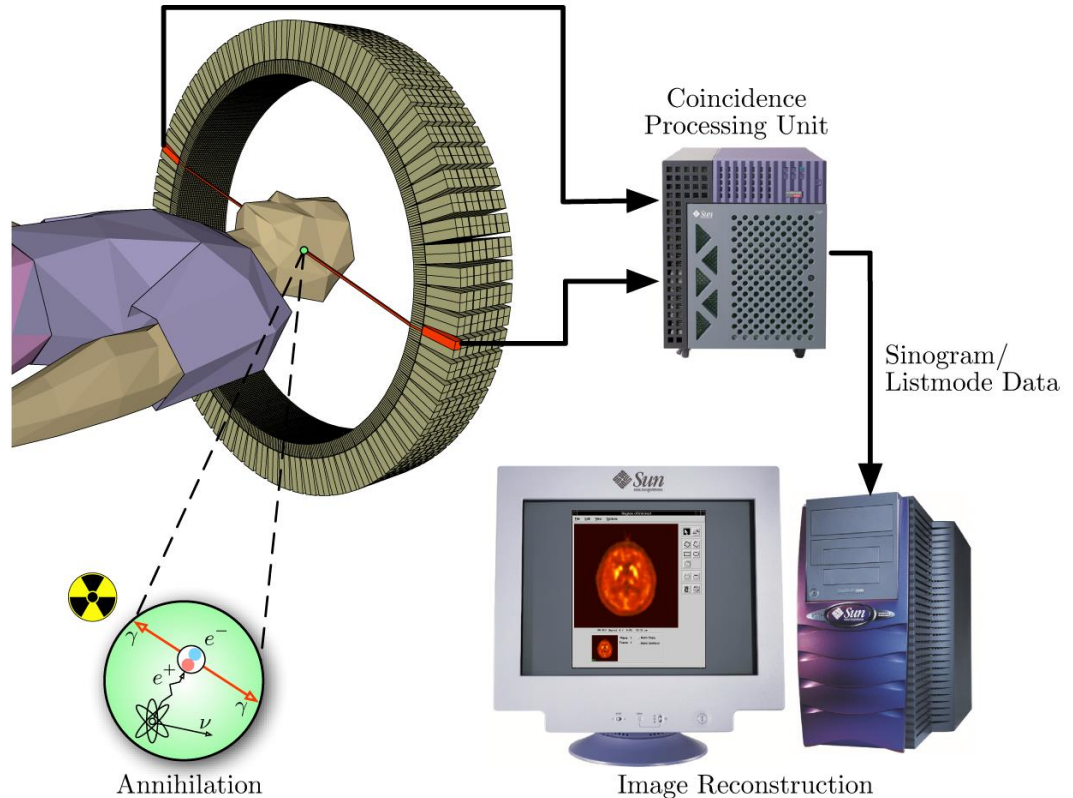
EFFICACY/QUALITY

COST/SIZE/EFFICIENCY

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

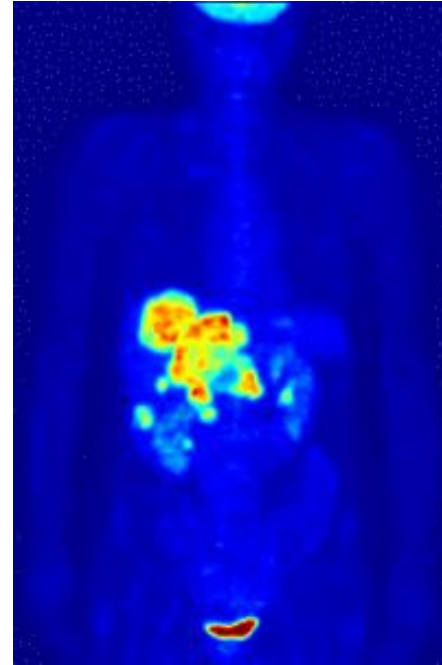
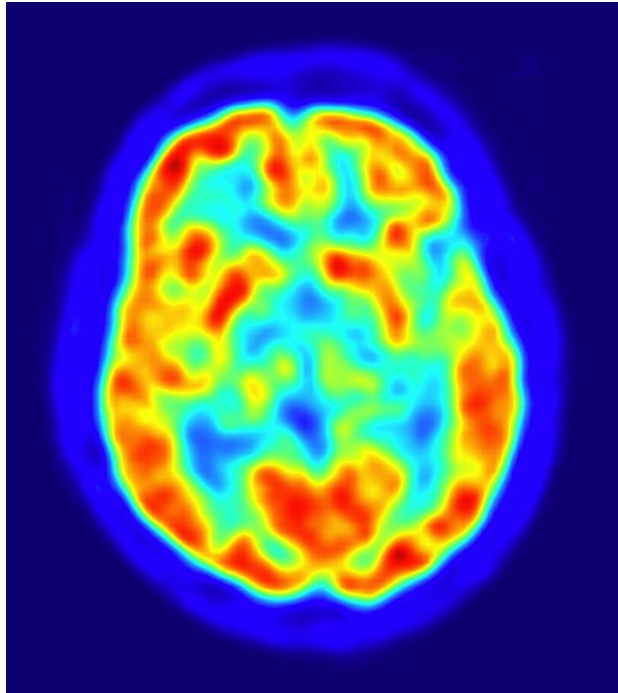
# Radioisotope production

- 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  $\sim 110$  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...

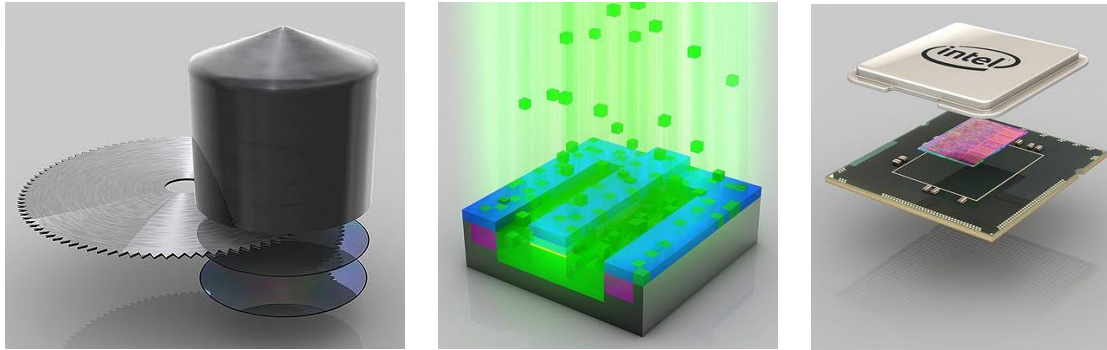


TABLE 2.1. THE RADIOISOTOPES THAT HAVE BEEN USED AS TRACERS IN THE PHYSICAL AND BIOLOGICAL SCIENCES

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

## 2. Industrial accelerators

# Ion implantation



Images courtesy of Intel

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

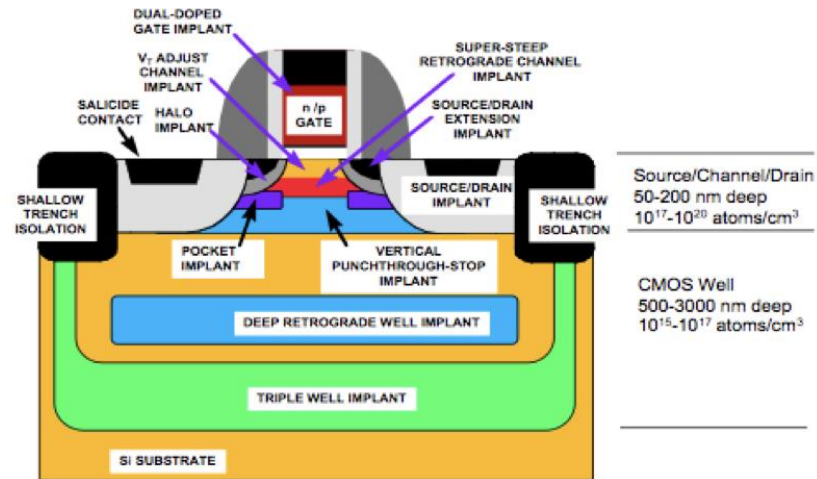


Figure 2: Sketch of major doped regions for a planar CMOS transistor.

# Electron beam processing

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

33% Wire cable tubing

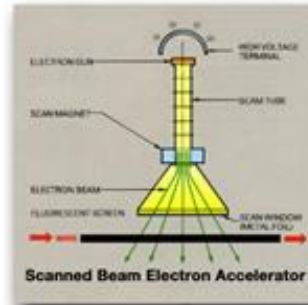
32% Ink curing

17% shrink film

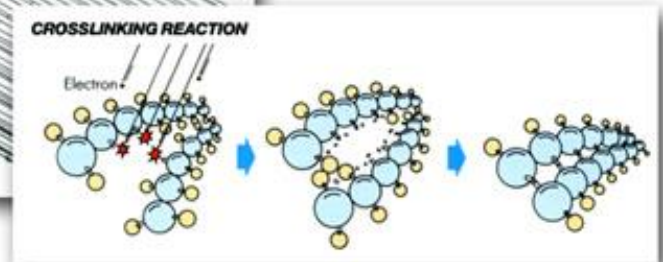
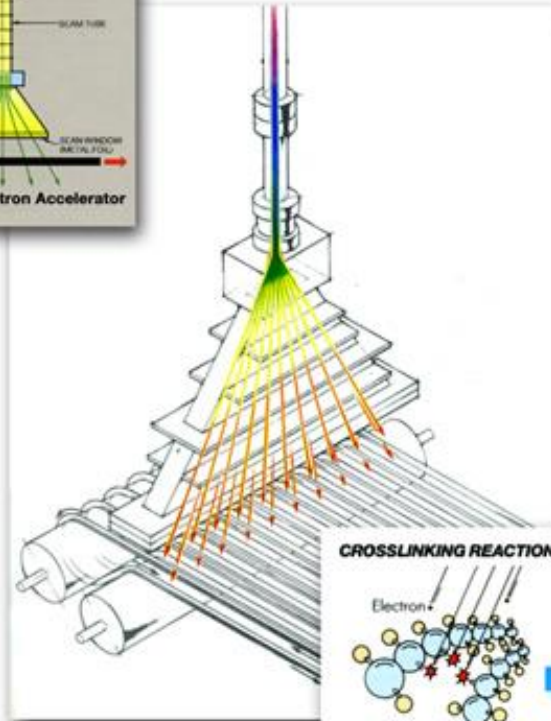
7% service

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)



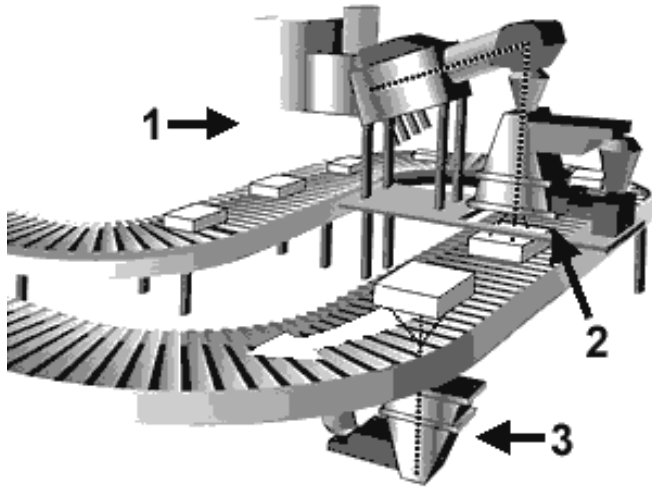
*40-50% of all disposable medical products manufactured in North America are currently radiation sterilized, primarily at 60Co irradiation facilities. – Hamm & Doyle, 2018*



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:

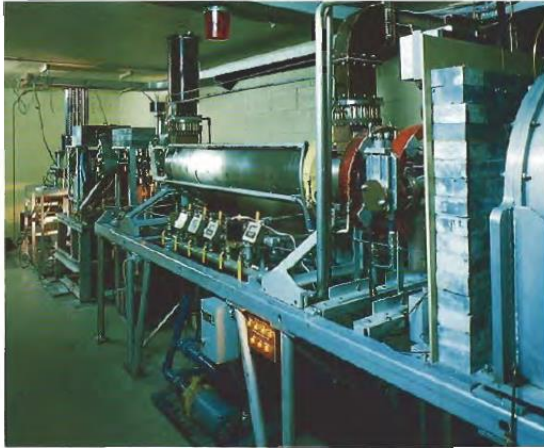


Lower dose



Higher dose

# Gemstone Irradiation



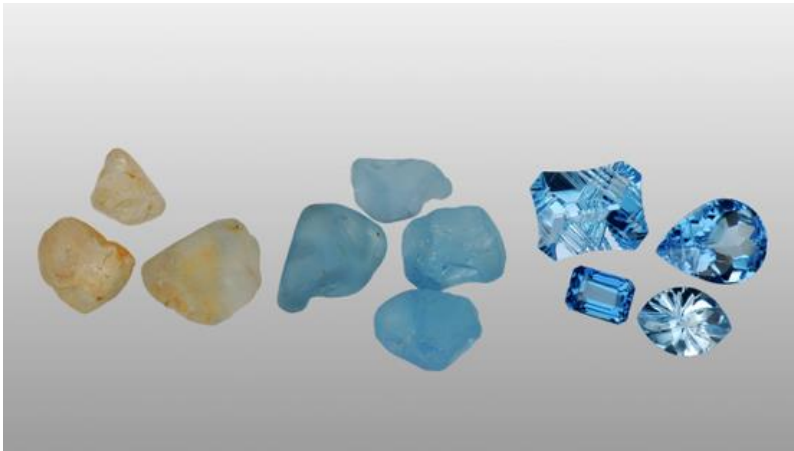
**TABLE 2.** Effects of irradiation treatment on various gem materials.<sup>a</sup>

Material	Starting color	Ending color
Beryl	Colorless Blue	Yellow Green
Maxixe-type	Pale or colorless	Blue
Corundum	Colorless Pink	Yellow 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 <sup>b</sup>	Colorless, "straw," pink, or light blue	Blue, lavender, amethyst, red
Spodumene	Colorless to pink	Orange, yellow, green, pink <sup>c</sup>
Topaz	Yellow, orange Colorless, pale blue	Intensify colors Brown, blue (may require heat to turn blue), green
Tourmaline	Colorless to pale colors Blue	Yellow, brown, pink, red, bicolor green-red Purple
Zircon	Colorless	Brown to red

<sup>a</sup>Adapted from Nassau (1984).

<sup>b</sup>Charles Key, pers. comm., 1988.

<sup>c</sup>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

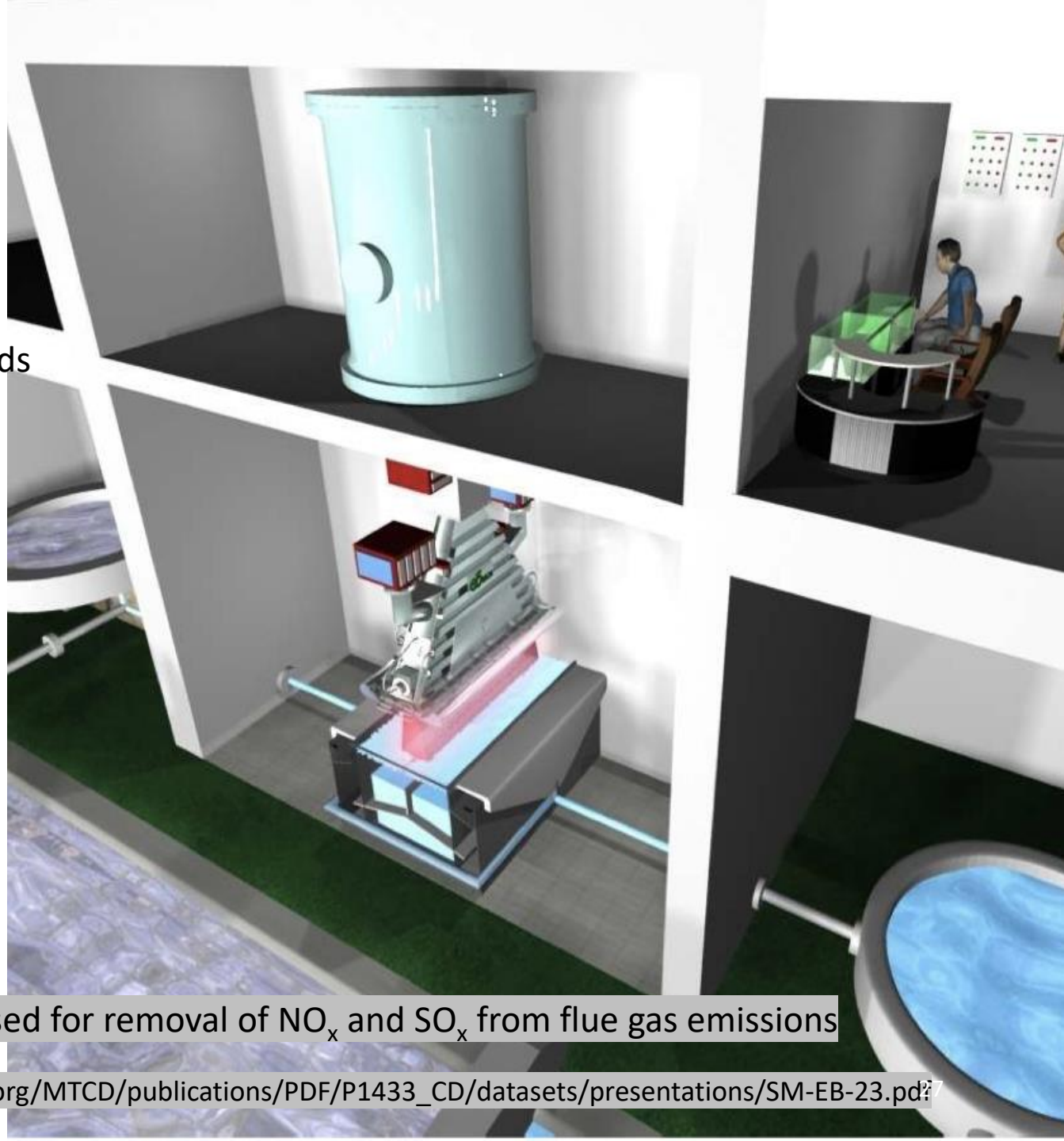
Remove organic compounds and disinfect wastewater.

Can be used to treat/reclaim:

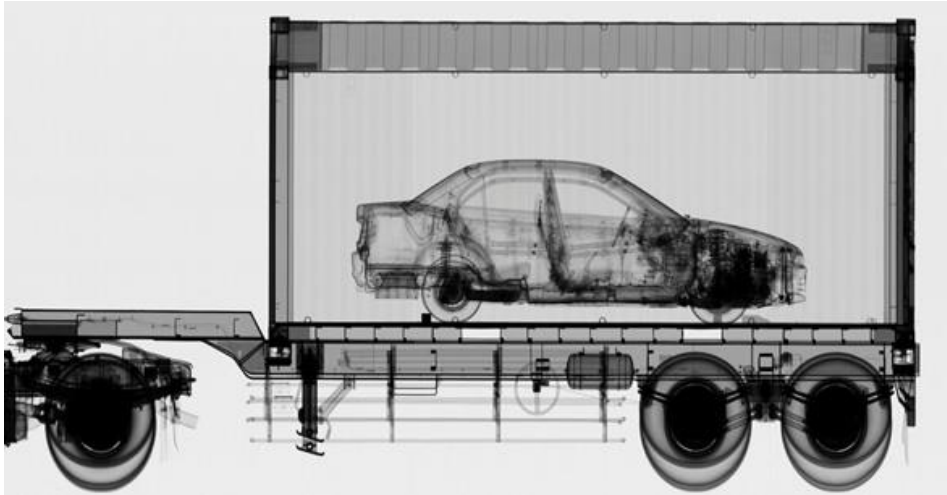
- Textile Dyeing
- Pharmaceutical
- Petrochemical
- Municipal Wastewater
- Contaminated Underground Water

1 MeV, High Current, scanning system

Also used for removal of  $\text{NO}_x$  and  $\text{SO}_x$  from flue gas emissions



# 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

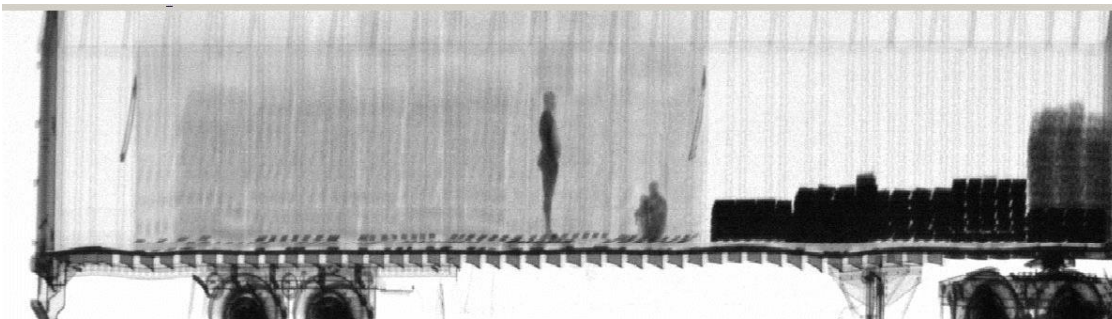


Image: dutch.euro



# Ion beam analysis

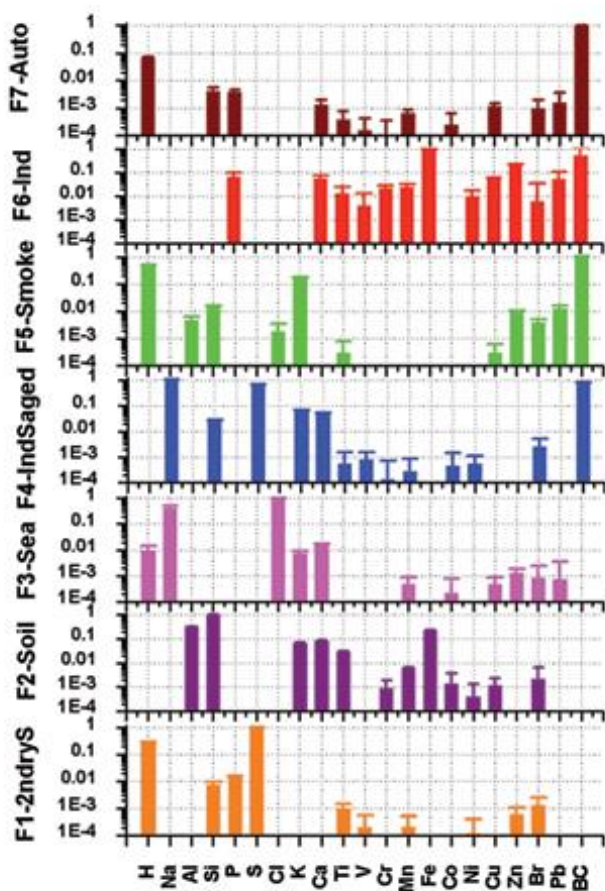
Bombarding with ions excites materials, which give off characteristic bursts of x-rays, gammas etc = a 'fingerprint' for elemental analysis.



ANSTO Centre for Accelerator Science

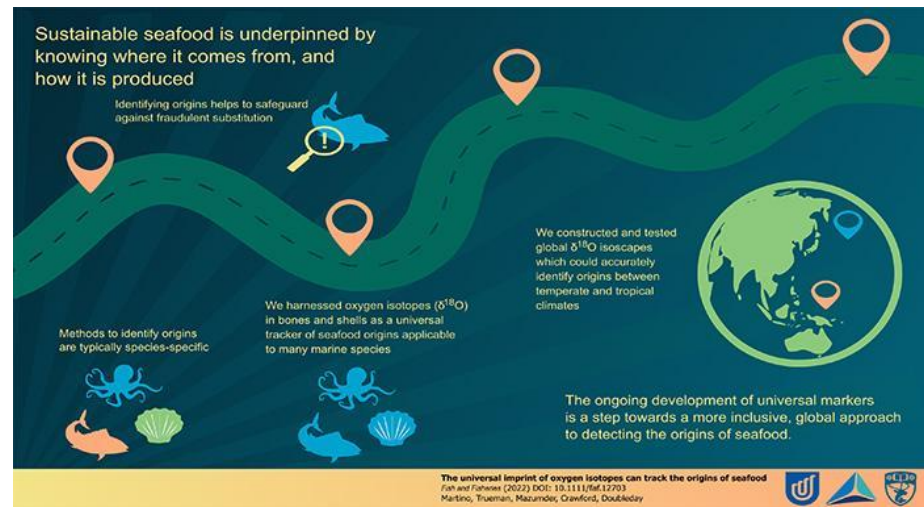
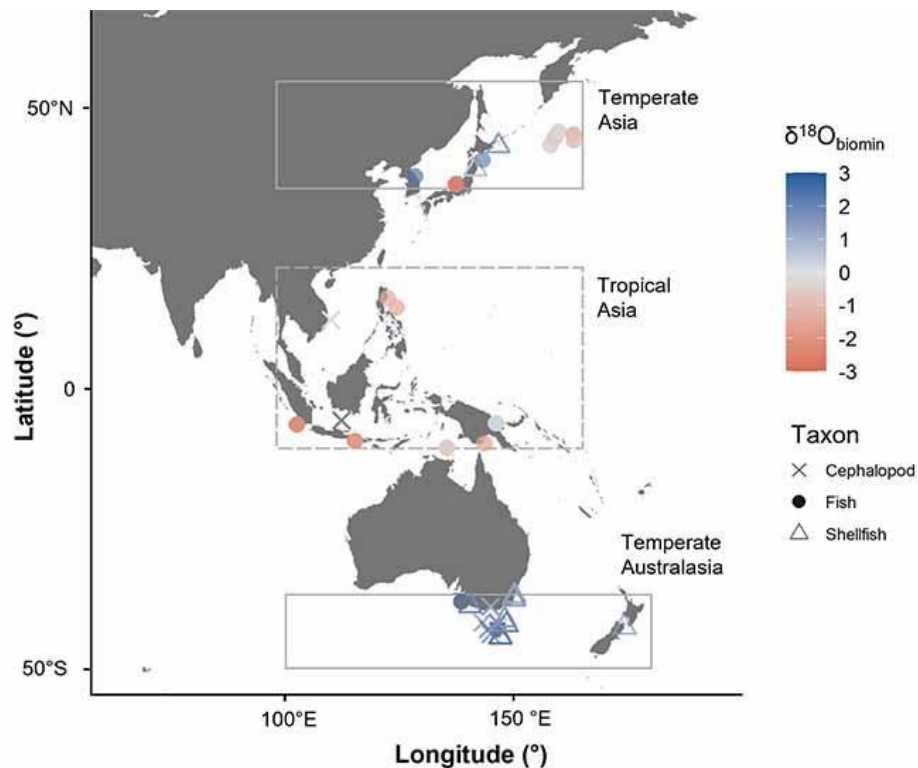
# Studying Aerosols and Pollutants

“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

# Emerging application: Food Provenance

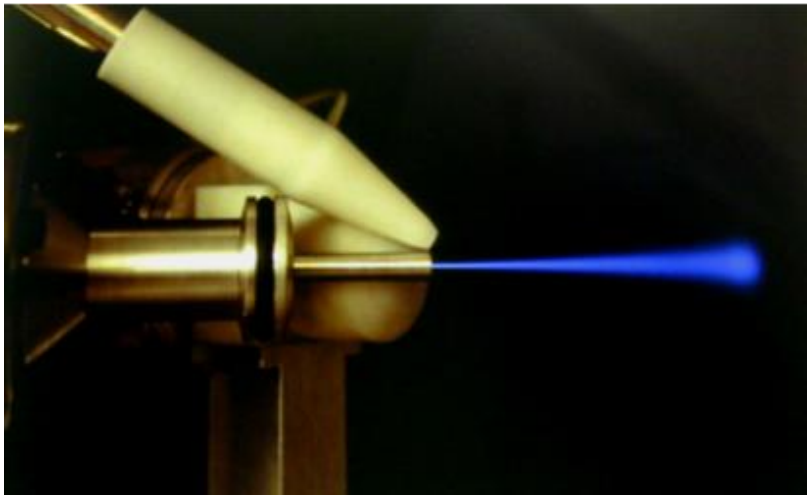


## 4. Historical and cultural applications

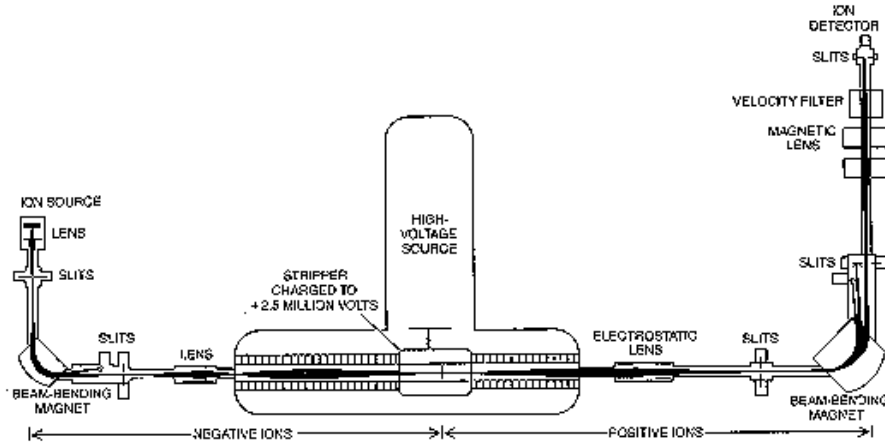


# IBA techniques in art

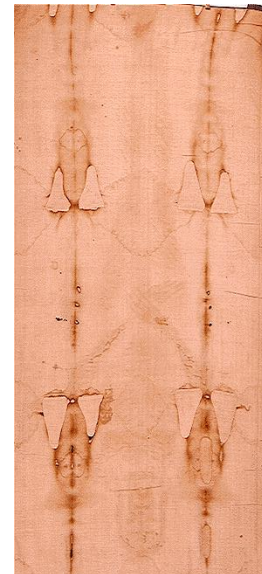
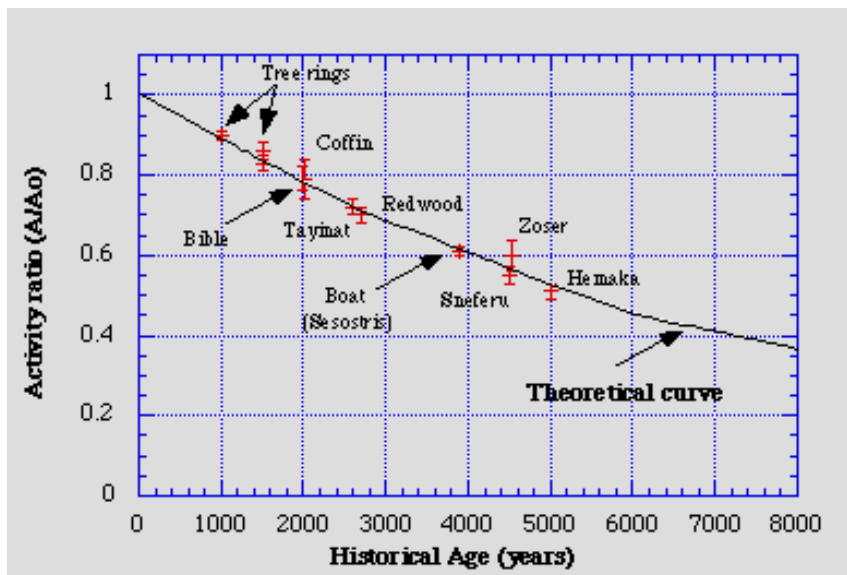
- Ion Beam Analysis (MeV) shows us the chemical composition of pigments used in paint
- Backscattered radiation can give detailed analysis of atoms present in surface.
- This allows art historians to compare them with paints available to artists like Leonardo da Vinci



# Accelerator Mass Spectrometry: Radiocarbon Dating



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



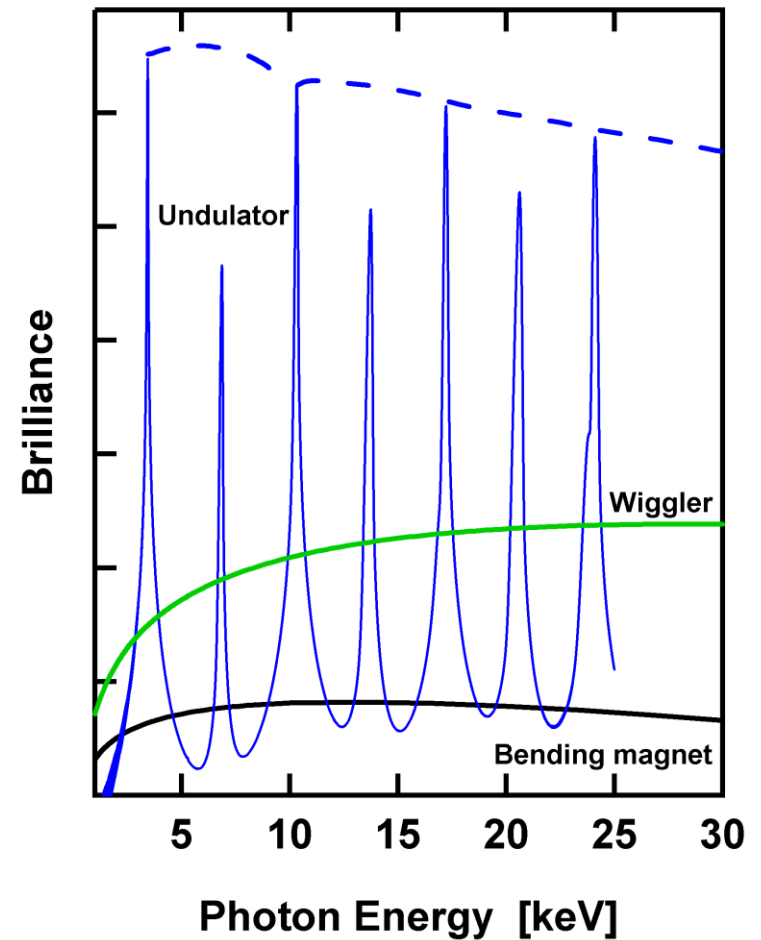
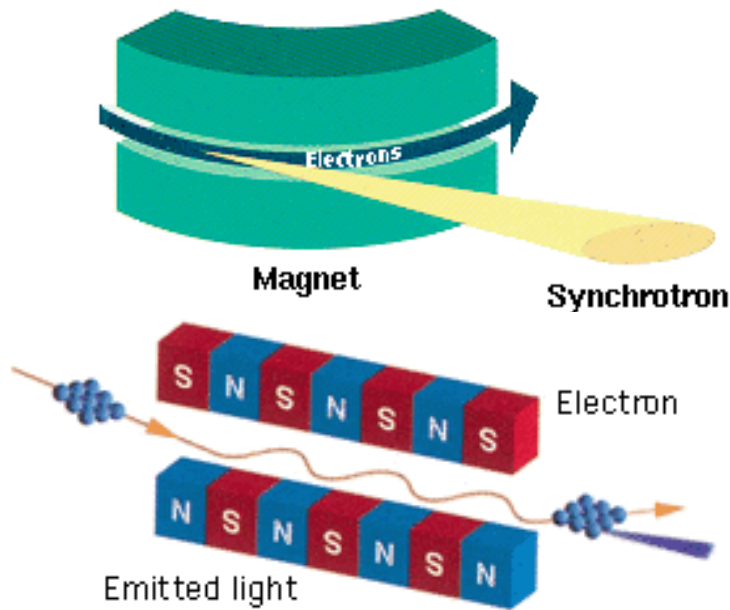
# 5. Synchrotron Light Sources



Image courtesy of ESRF



Synchrotron radiation is emitted by charged particles when accelerated radially

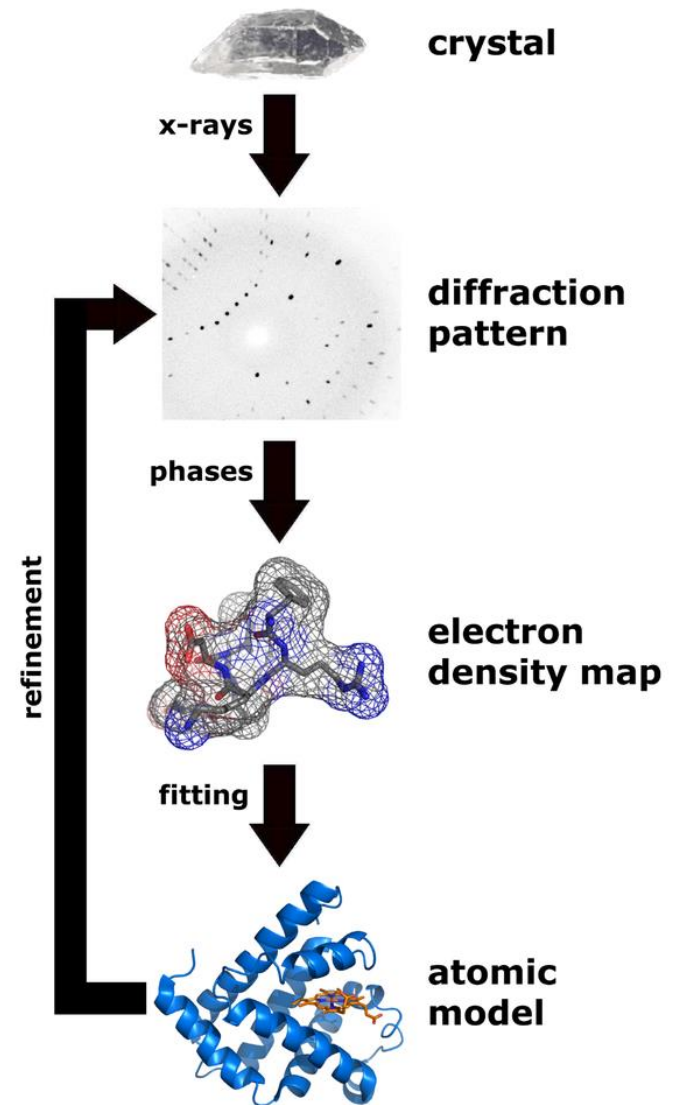


Produced in synchrotron radiation sources using bending magnets, undulators and wigglers

# X-Ray crystallography

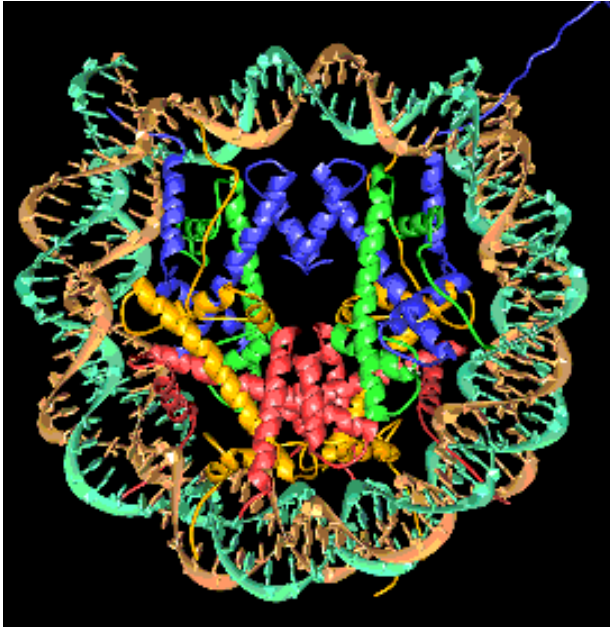
Protein crystallography is a standard technique at synchrotron light sources (Diamond light source has 5 beamlines devoted to it)

The hardest part is forming the crystal...

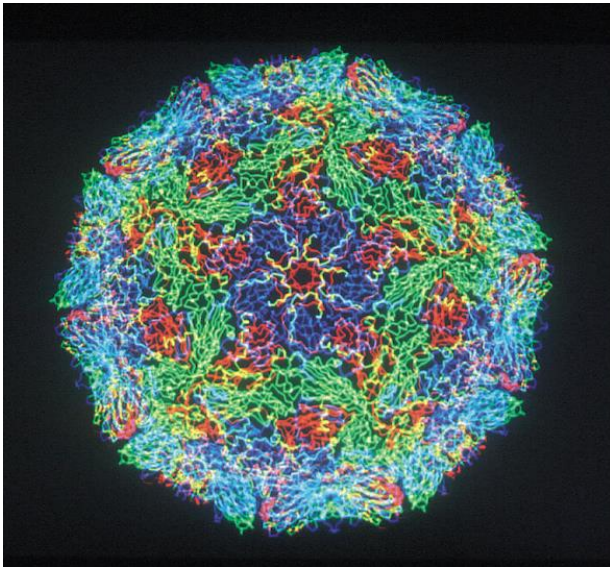


For some great overview videos of crystallography, see:  
<http://www.richannel.org/collections/2013/crystallography>

# Structural Biology

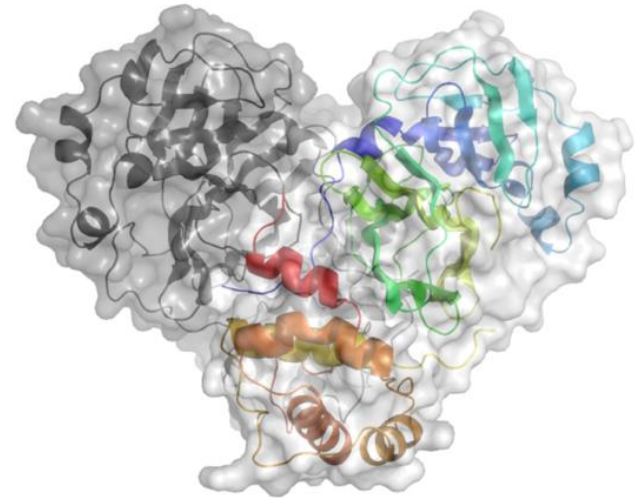


Reconstruction of the 3D structure of a nucleosome (DNA packaging) with a resolution of 0.2 nm



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.

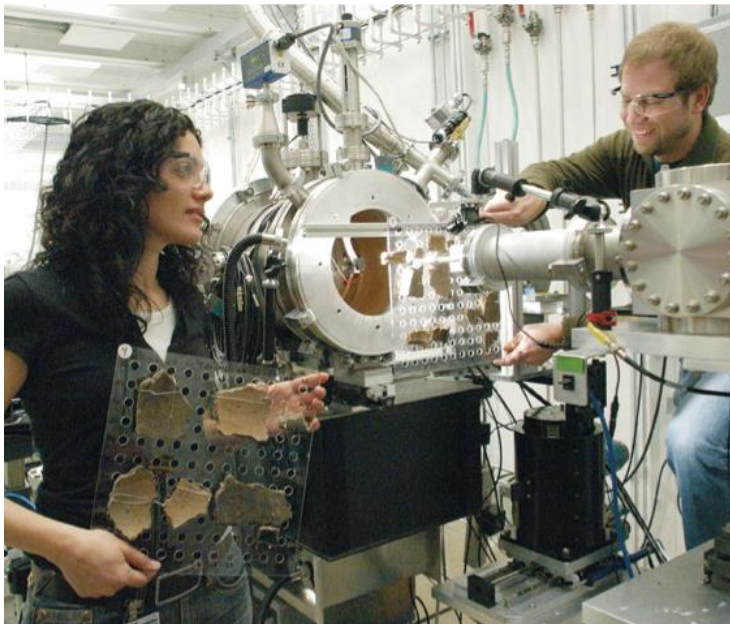


Image: Argonne National Laboratory



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

# X-rays also used to study art

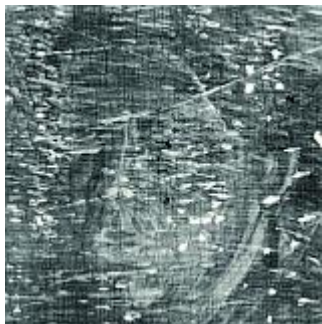


*Patch of Grass*, spring 1887, F583/JH1263, KM 105.264 (30,8 x 39,7 cm), Kröller-Müller Museum  
(Photo: Rik Klein Gotink)

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





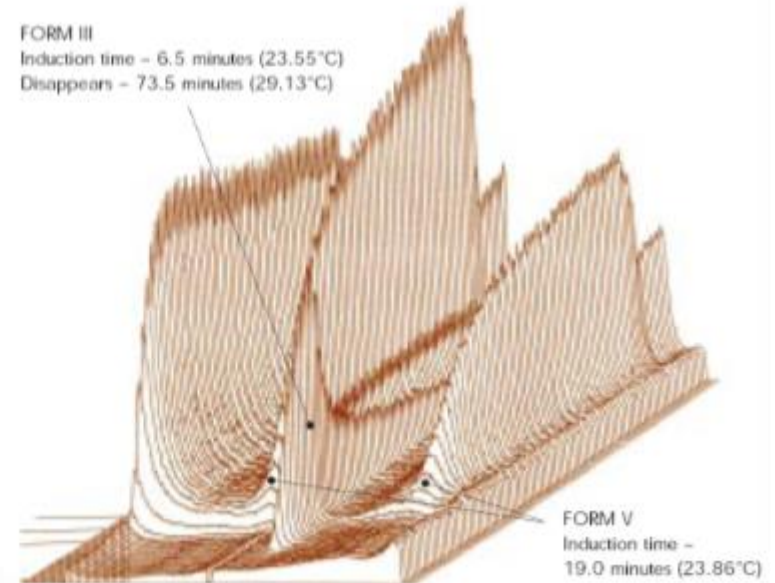
# Crystal structure formation

NEW INSIGHTS INTO  
**CHOCOLATE**

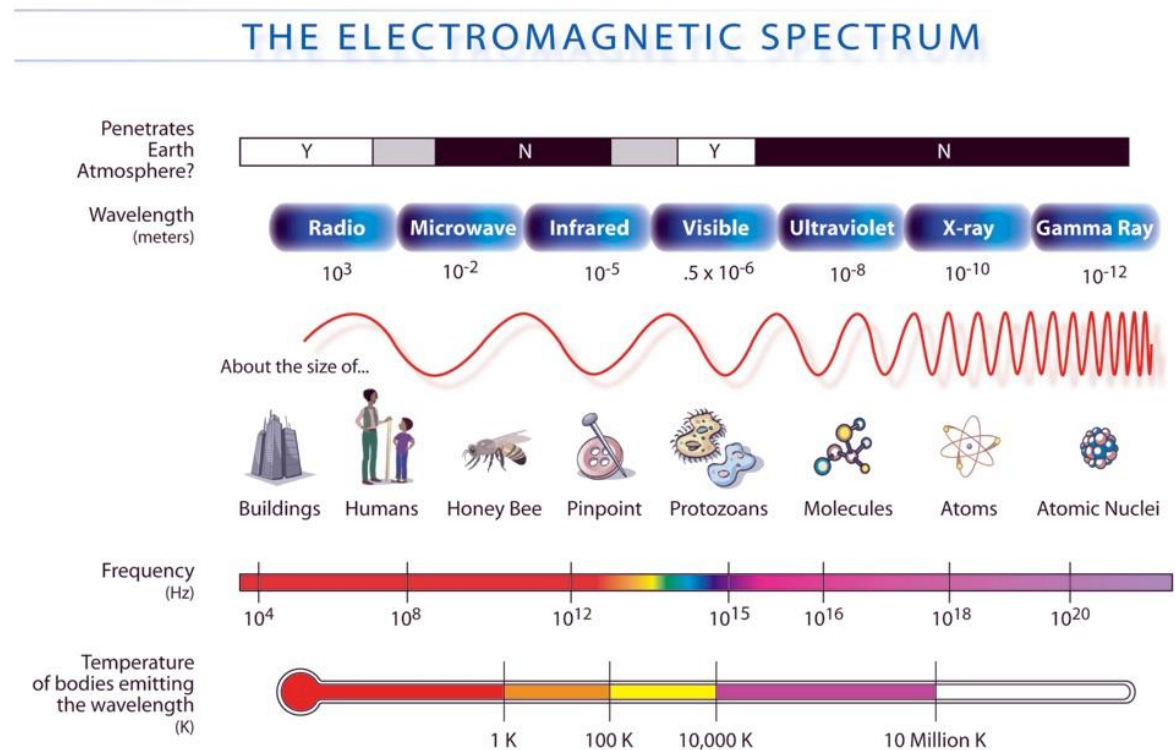


Of the six possible crystal forms, the fifth (form V) produces the best quality chocolate

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)

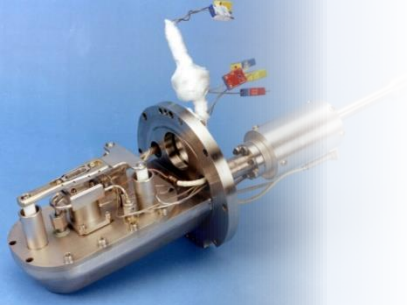




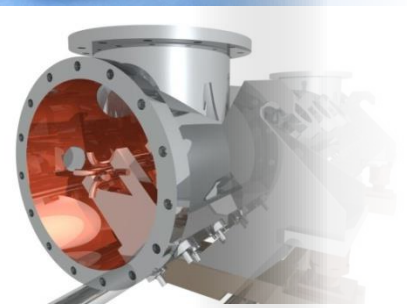
Hard condensed matter science  
Applied material science  
Engineering  
Chemistry  
Soft condensed matter science  
Life sciences  
Structural biology  
Medicine  
Earth and science  
Environment  
Cultural heritage  
Methods and instrumentation

## 6. Neutron Spallation Sources





# From Protons to Neutrons: Spallation Sources



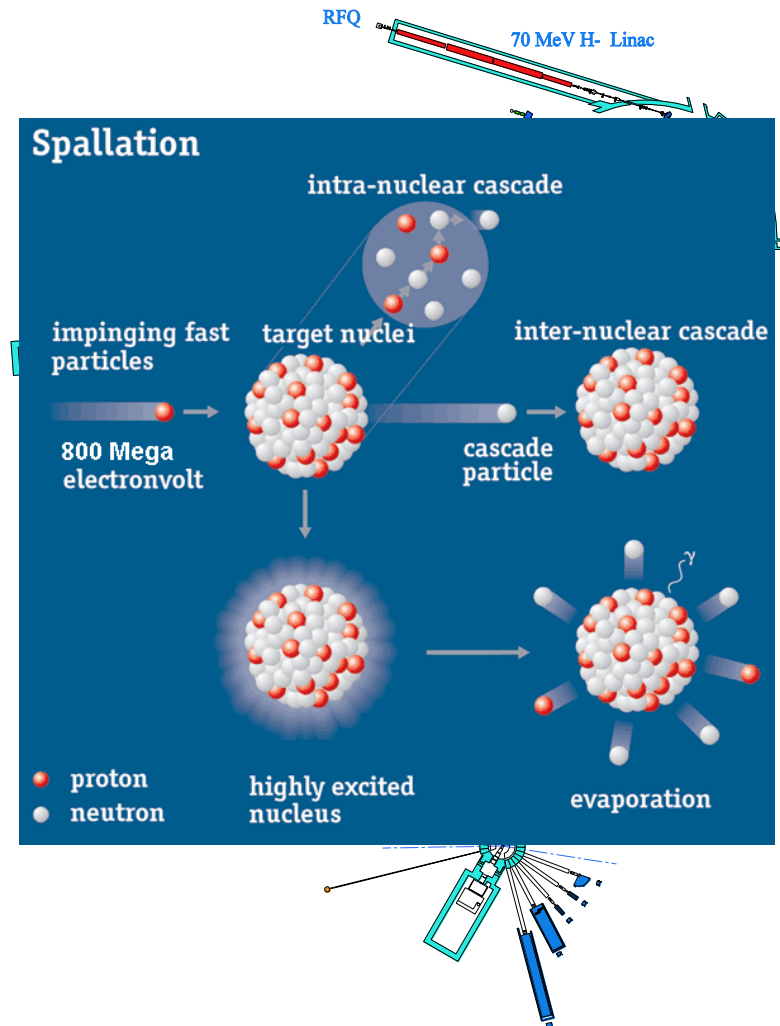
ISIS neutron spallation source:  
RFQ, linac, 800 MeV proton  
synchrotron



Pulsed beam of 800 MeV  
(84% speed of light) protons  
at 50 Hz  
Average beam current  
is 230  $\mu\text{A}$  ( $2.9 \times 10^{13}$  ppp)



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



$$P = 800[MV] \cdot 230[mA] = 184[kW]$$





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

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

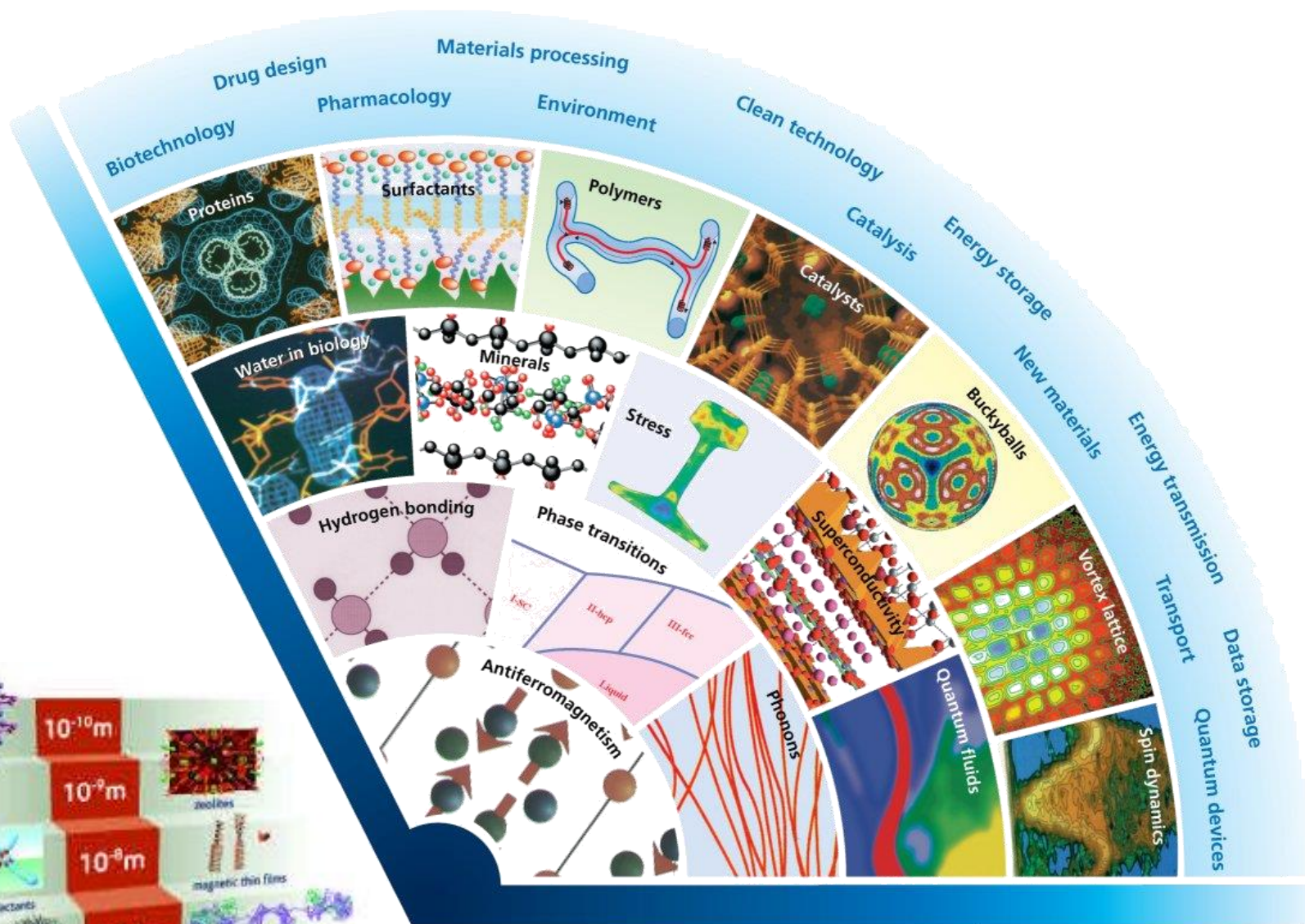
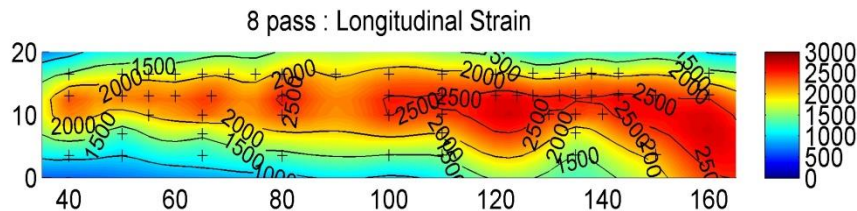
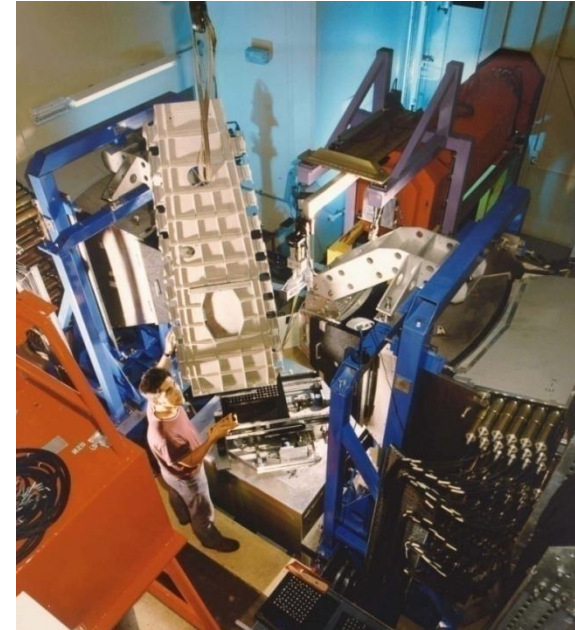


Image courtesy ISIS, STFC.

# 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

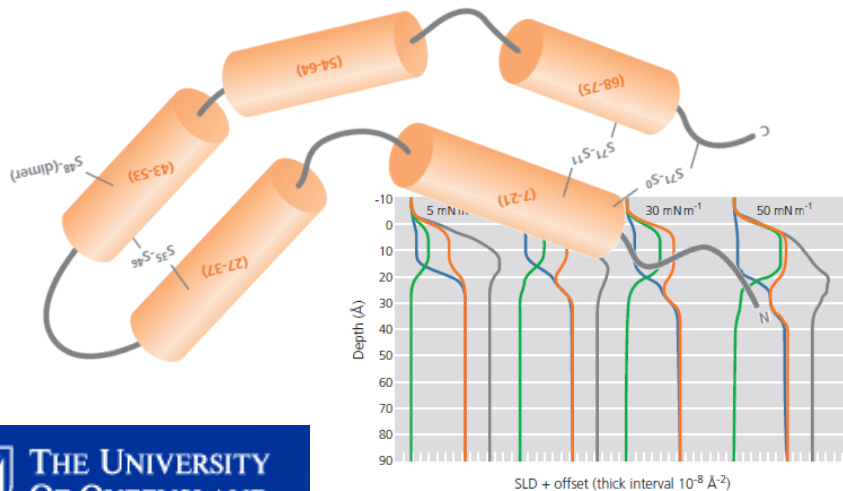


“Residual stress measurement at ISIS has been invaluable in researching and developing existing and novel material manufacturing and processing techniques .”  
– Richard Burguete, Airbus Experimental Mechanics Specialist



# 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

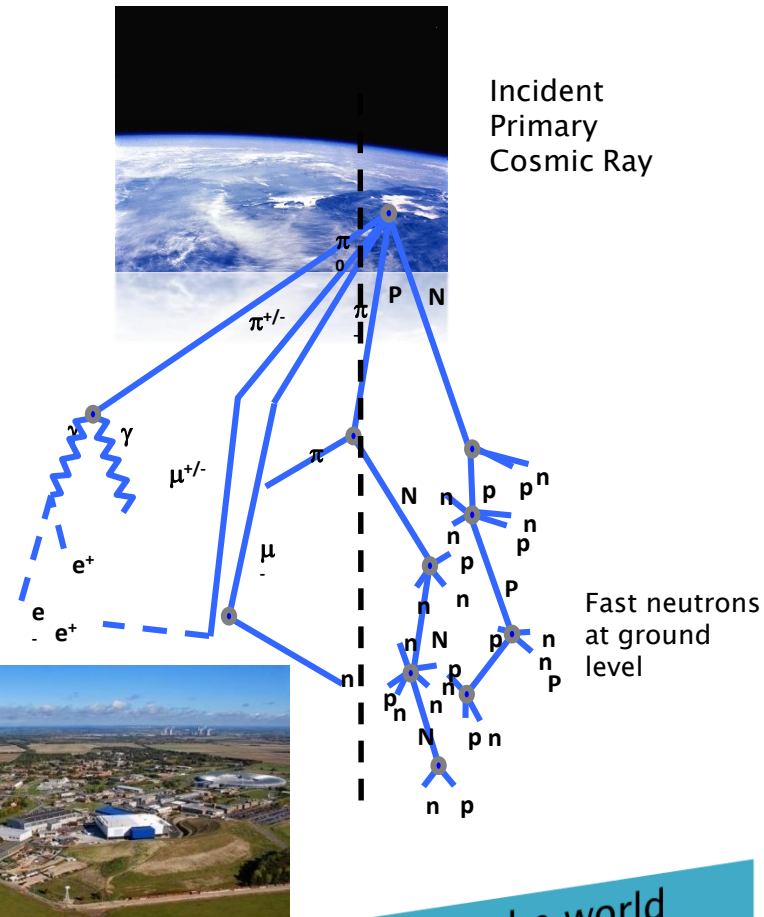


"ISIS is the premier place in the world to work with neutrons and liquid surfaces. In collaboration with the University of Queensland we were able to discover how proteins and phospholipids act together to enable lung function."

- 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



# 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

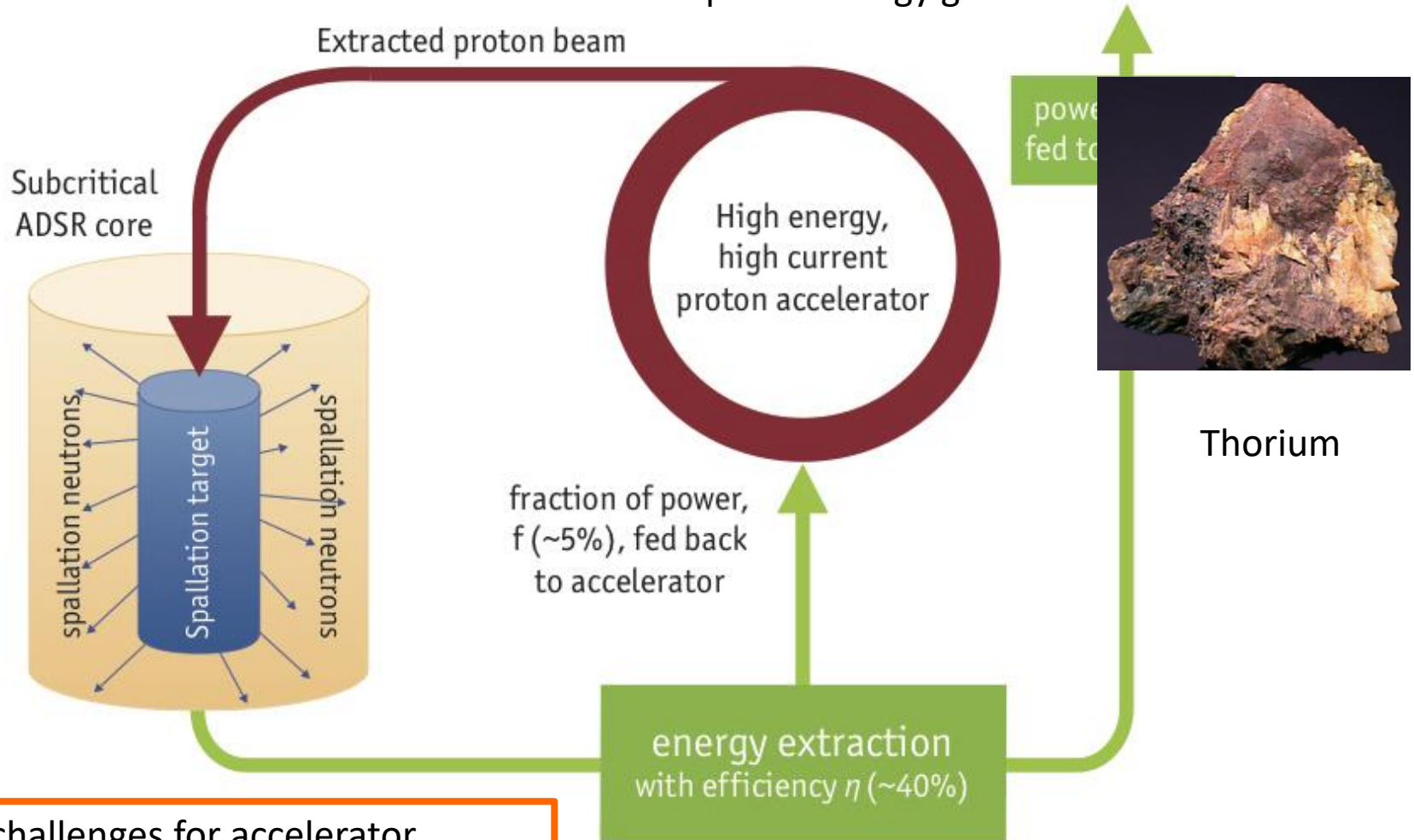
To de-risk IFMIF, first a test accelerator  
'LIPAc' is being built



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

# 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

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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

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

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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