Applications of Accelerators

CERN Introductory Accelerator School
Vyosoke Tatry, Slovakia, 2019

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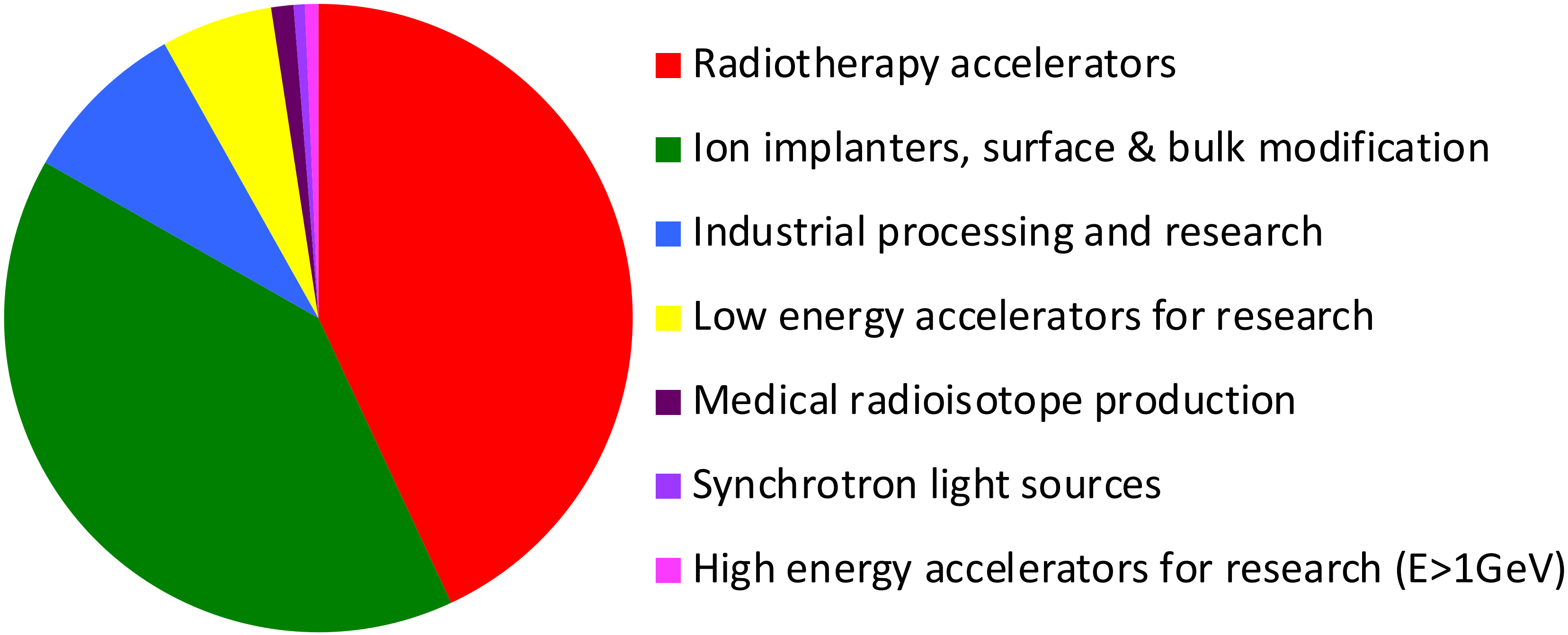
Royal Society University Research Fellow, University of Oxford

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

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



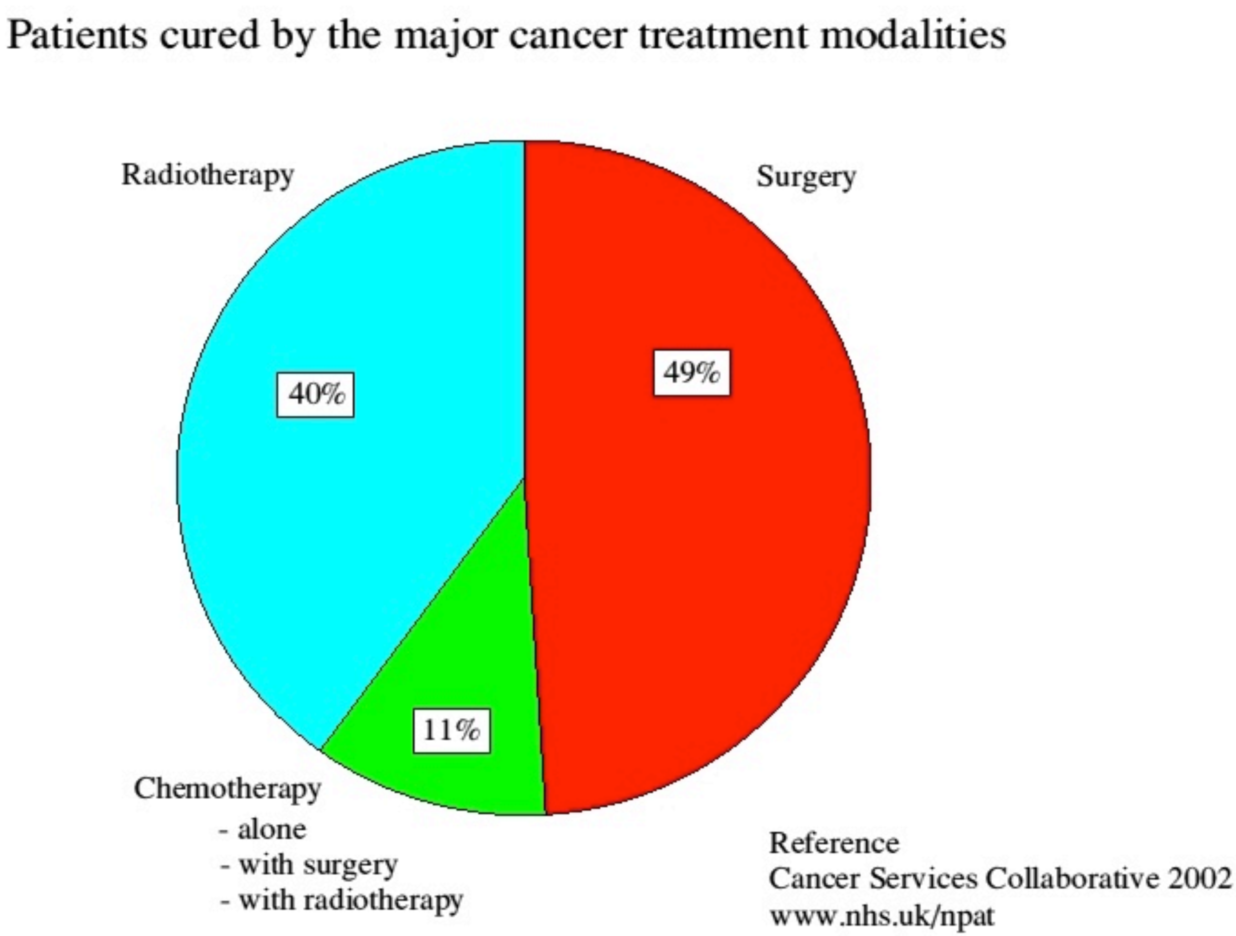
There are roughly 35,000 accelerators in the world
(Above 1 MeV...)

Outline

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

1. Medical Applications

- Around 1/3 of people in the will die from cancer…
- But diagnosis is no longer a death sentence!



X-ray radiotherapy

Linac

Foil to produce x-rays

Collimation system

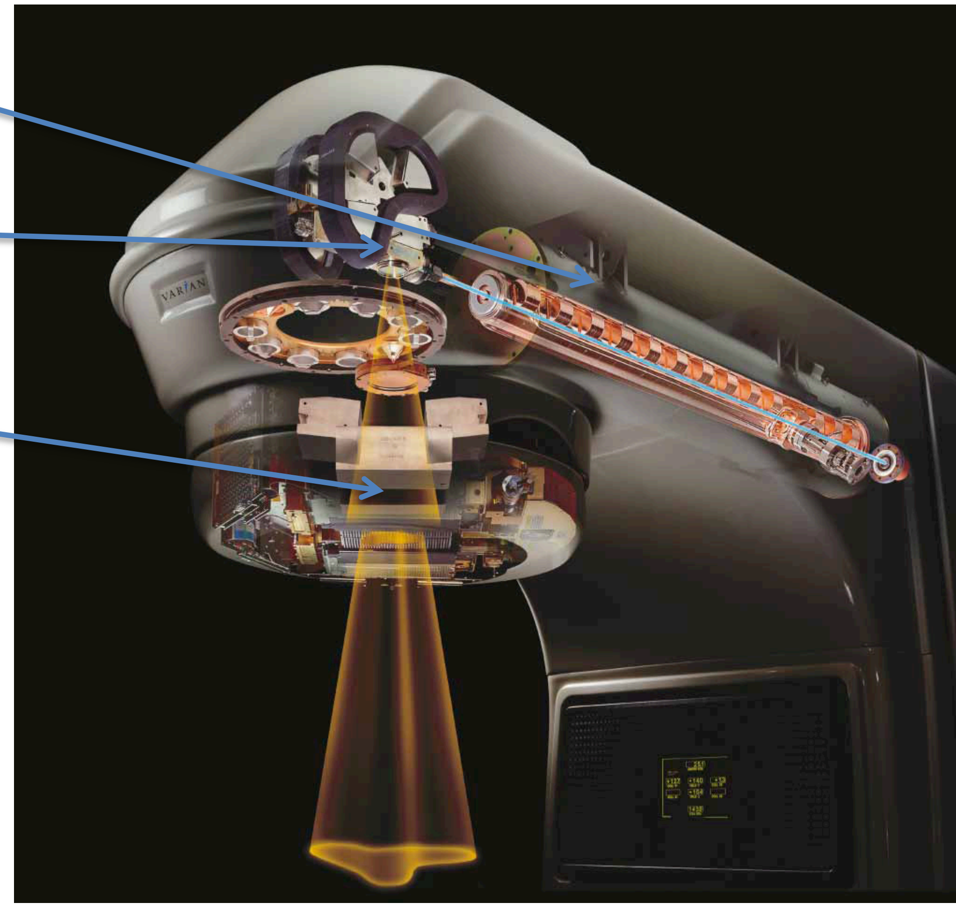
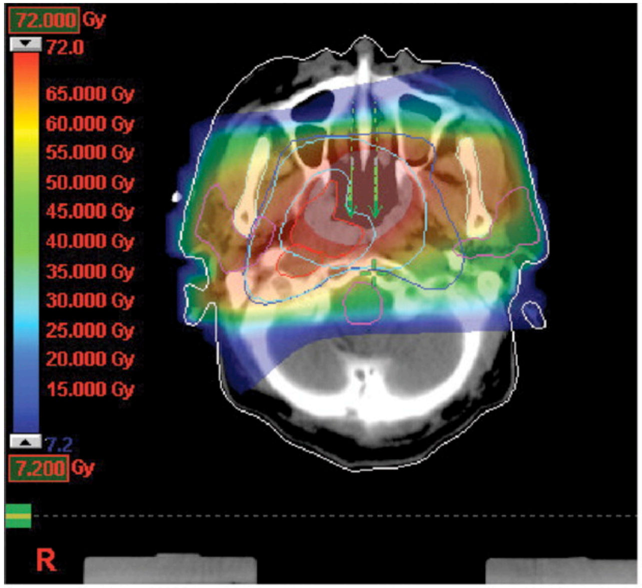


Image: copyright Varian medical systems


72.000 Gy
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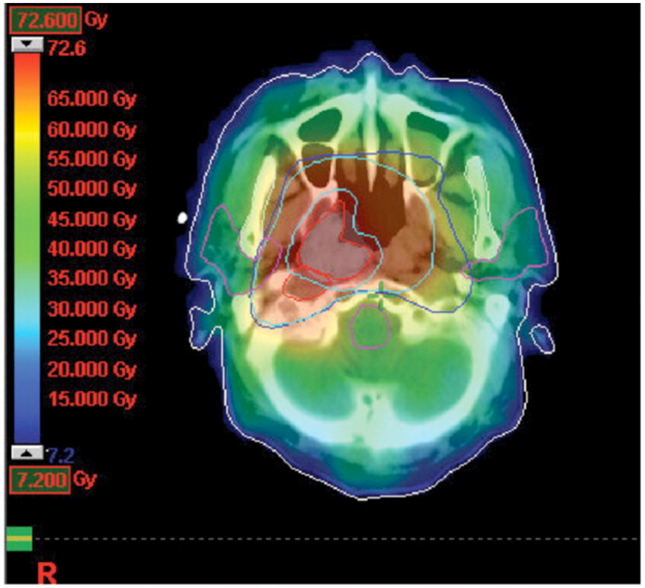
20.000 Gy
15.000 Gy
7.2
7.200 Gy
R

(a)


72.600 Gy
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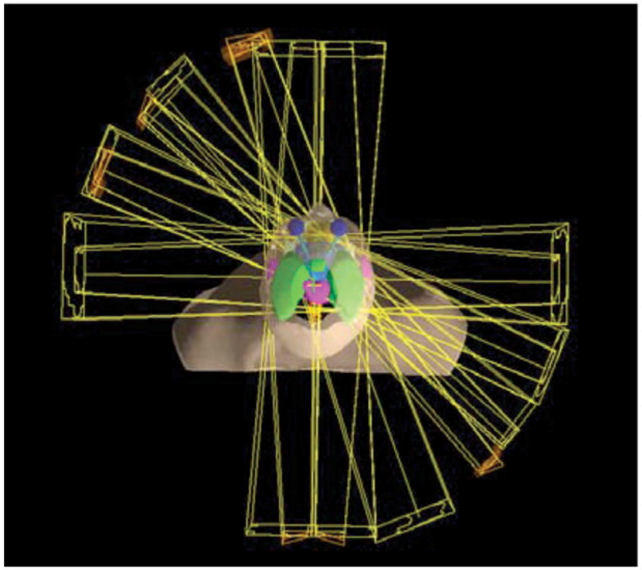
(b)



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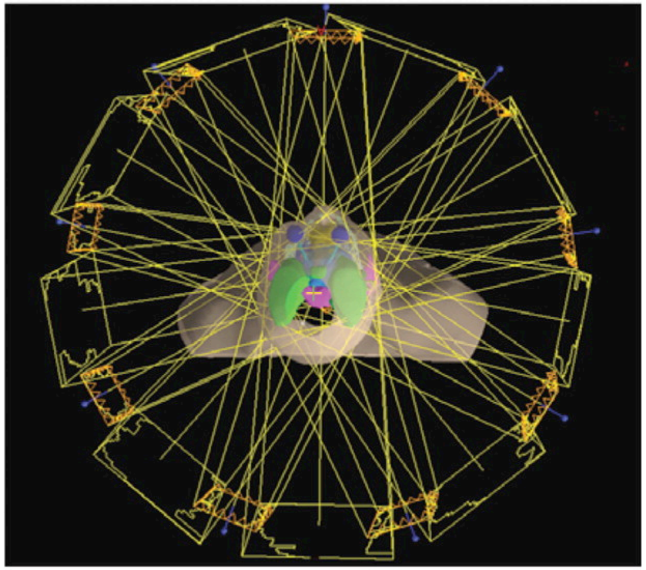
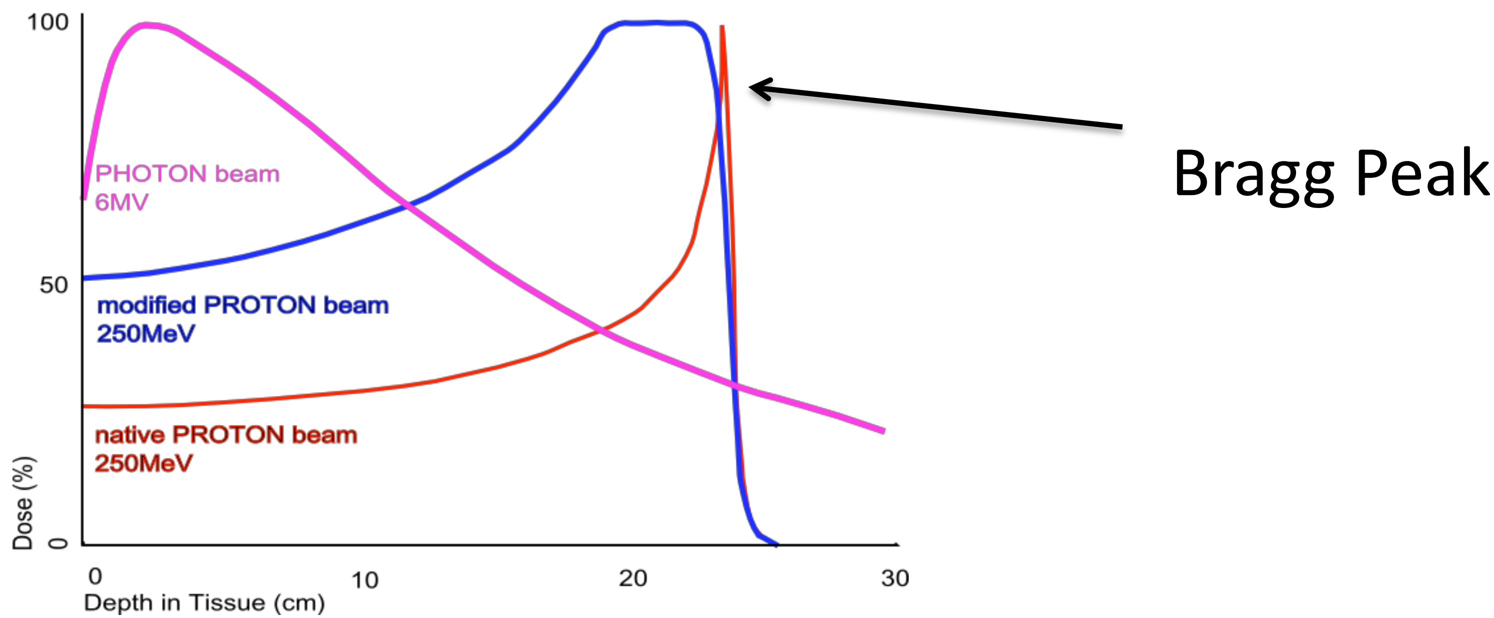


(d)

Charged Particle Therapy



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

Energy loss in materials

The relativistic version of the formula reads:

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

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

where

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

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

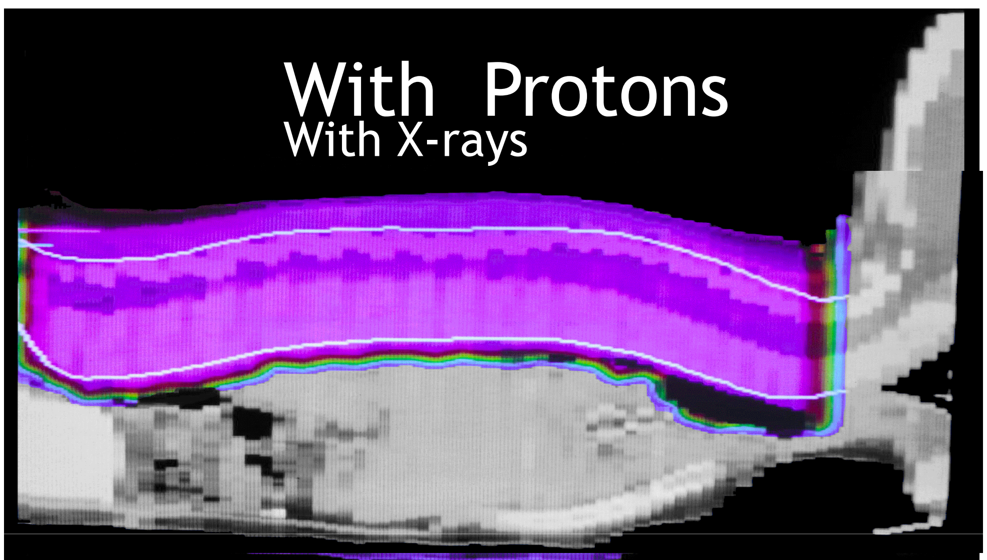
I mean excitation potential of the target

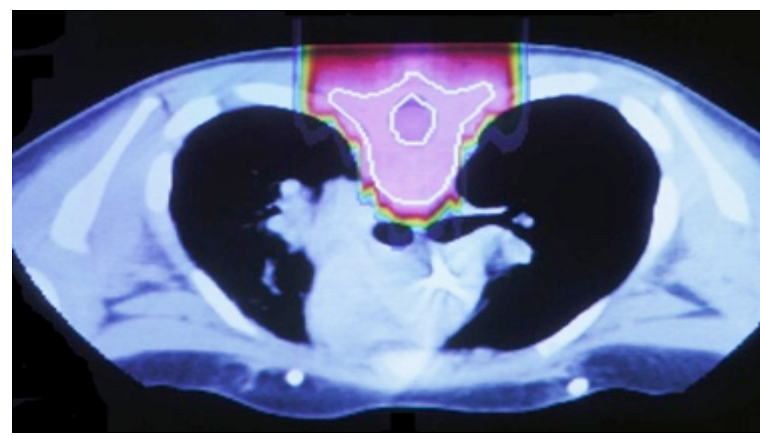
ε_0 vacuum permittivity

Proton therapy

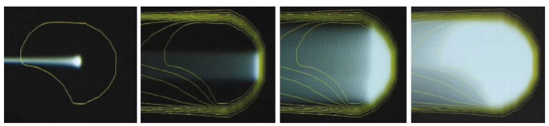
- "Hadron therapy" = Protons and light ions

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



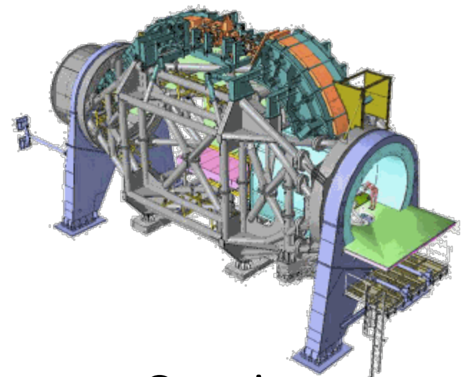


A few developments

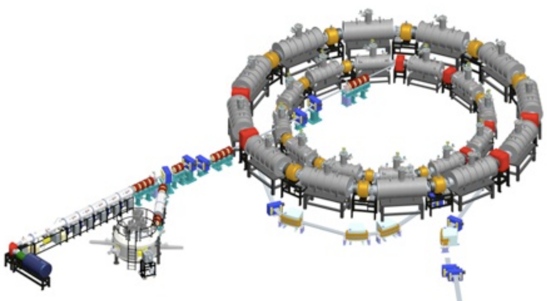


Spot Scanning

Proton Radiography

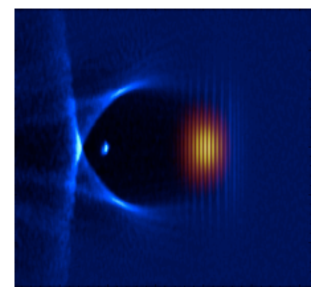


Gantries



FFA Accelerators

Dielectric Wall
Accelerators

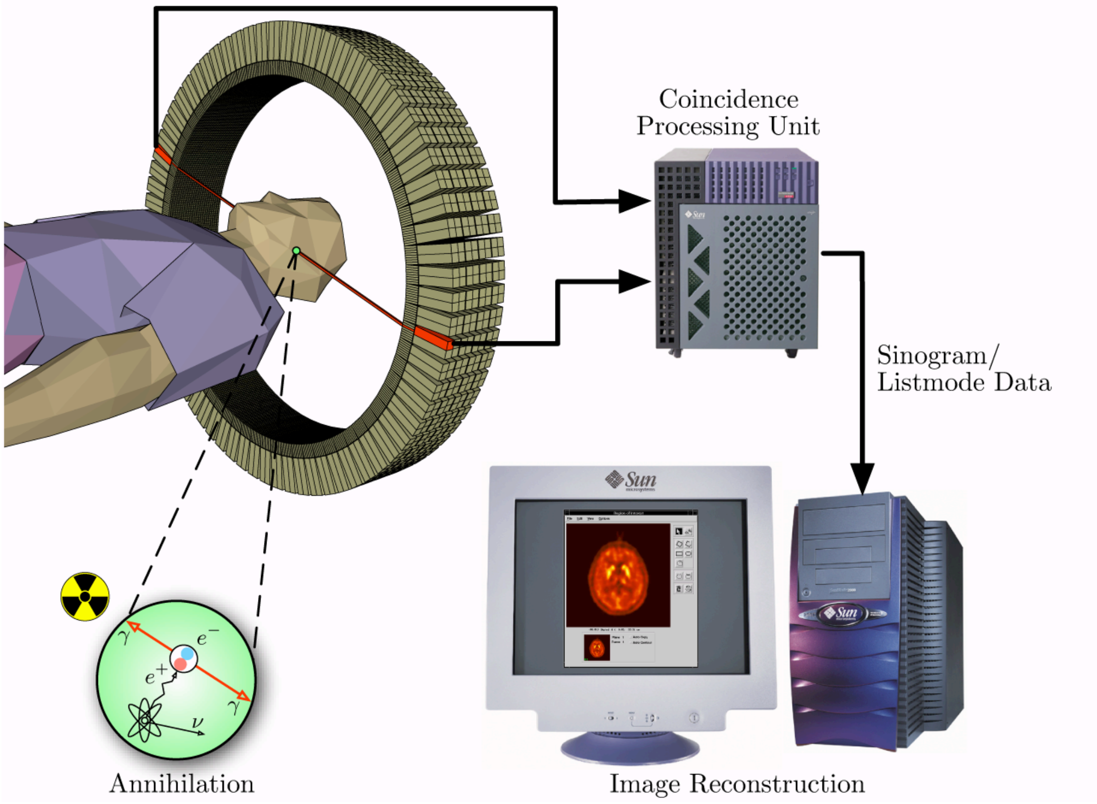


Laser Plasma
Accelerators

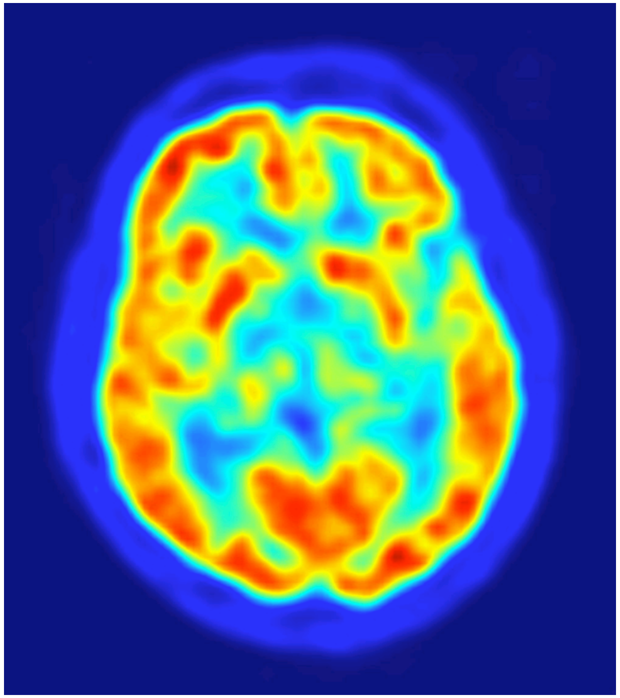
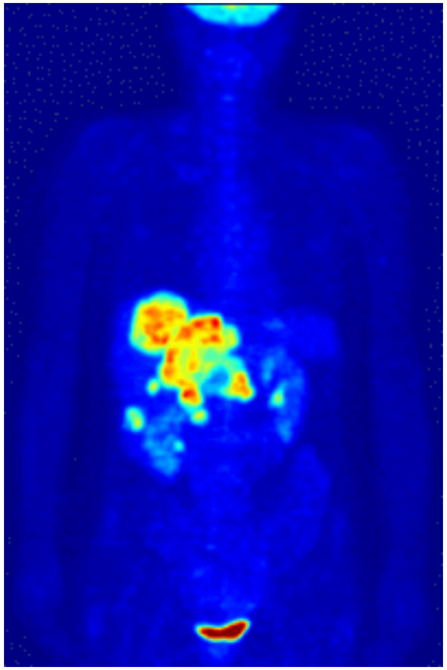
HEP community can contribute accelerators AND other expertise!

Radioisotope production

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



- Positron emission tomography (PET) uses Fluorine-18, half life of ~110 min

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

Radiopharmaceuticals

p, d, 3He, 4He
beams

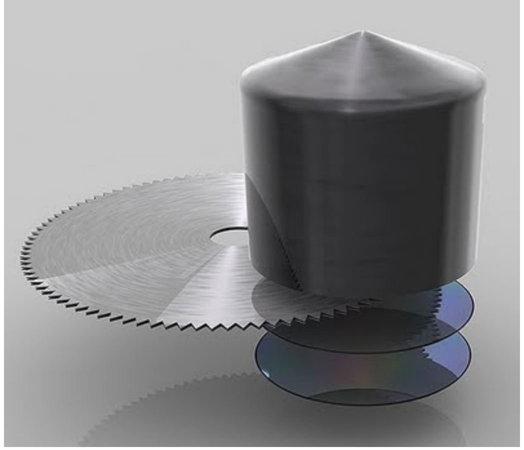
Isotopes used for PET, SPECT and Brachytherapy etc…

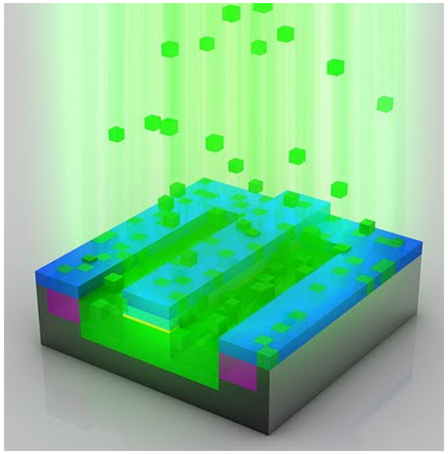
TABLE 2.1. THE RADIOISOTOPES THAT HAVE BEEN USED AS TRACERS IN THE PHYSICAL AND BIOLOGICAL SCIENCES

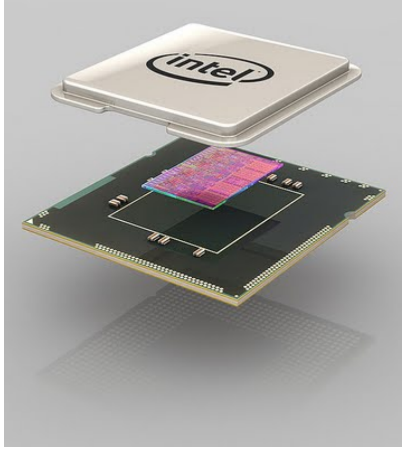
Isotope	Isotope	Isotope
Actinium-225	**Fluorine-18**	**Oxygen-15**
Arsenic-73	**Gallium-67**	**Palladium-103**
Arsenic-74	**Germanium-68**	**Sodium-22**
Astatine-211	Indium-110	**Strontium-82**
Beryllium-7	**Indium-111**	Technetium-94m
Bismuth-213	Indium-114m	**Thallium-201**
Bromine-75	Iodine-120g	Tungsten-178
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





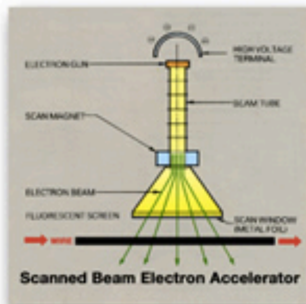


Images courtesy of Intel

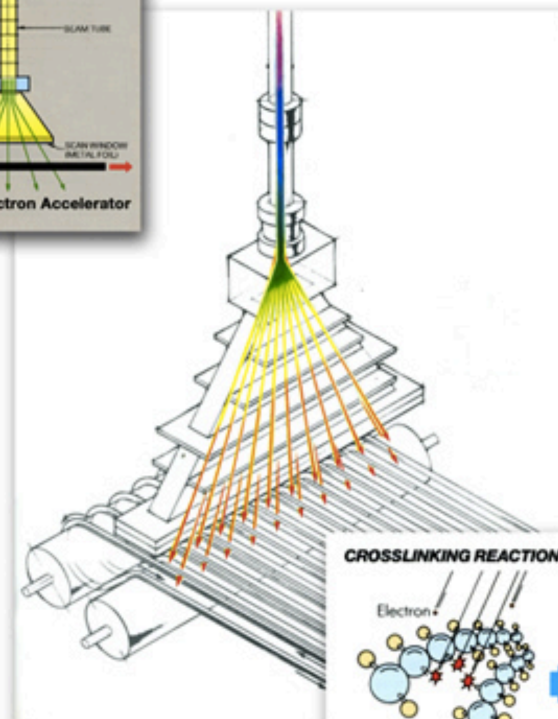
- Electrostatic accelerators are used to deposit ions in semiconductors.

Electron beam processing

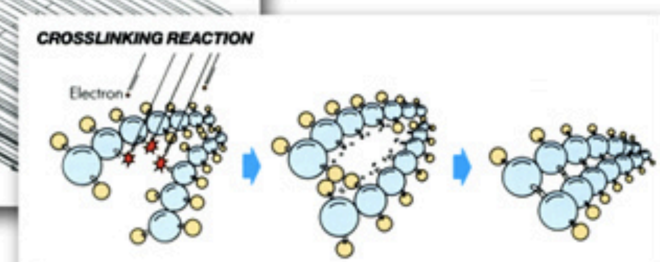
In the US, potential markets for industrial electron beams total \$50 billion per year.



http://rsccnuclearcable.com/capabilities.htm



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

Equipment sterilisation

Manufacturers of medical disposables have to kill every germ on syringes, bandages, surgical tools and other gear, without altering the material itself.

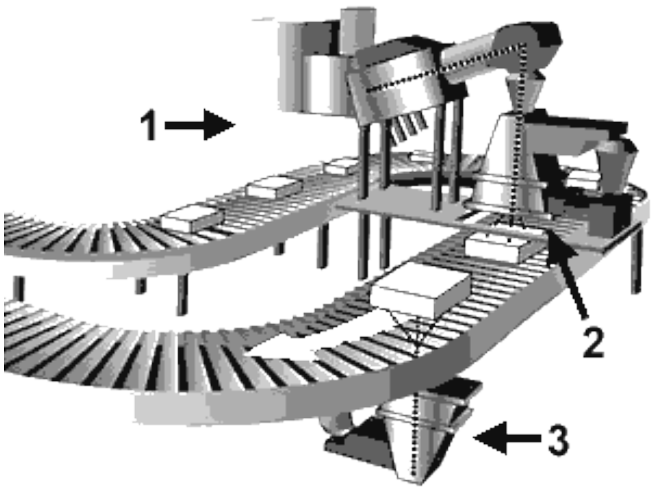
E-beam sterilisation works best on simple, low density products.

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

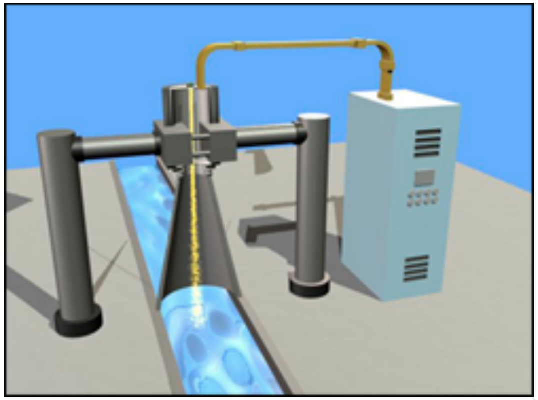
Foods authorised for irradiation in the EU:

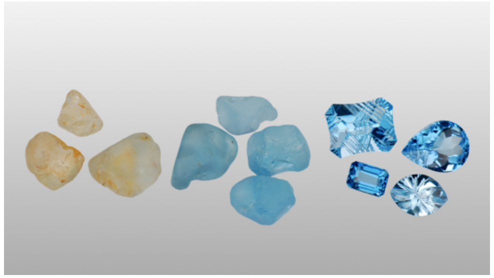
Lower dose → Higher dose

Other uses in industry…

- Hardening surfaces of artificial joints
- Removal of NO_x and SO_x from flue gas emissions
- Scratch resistant furniture

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





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

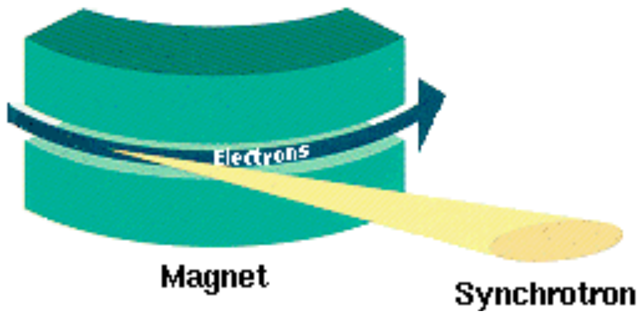
http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/irradiated-gemstones.html

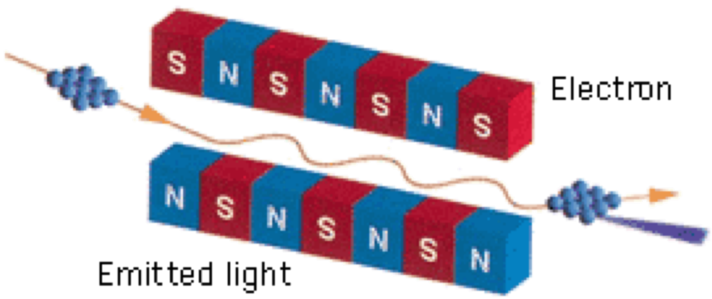
http://www.symmetrymagazine.org/article/october-2009/cleaner-living-through-electrons

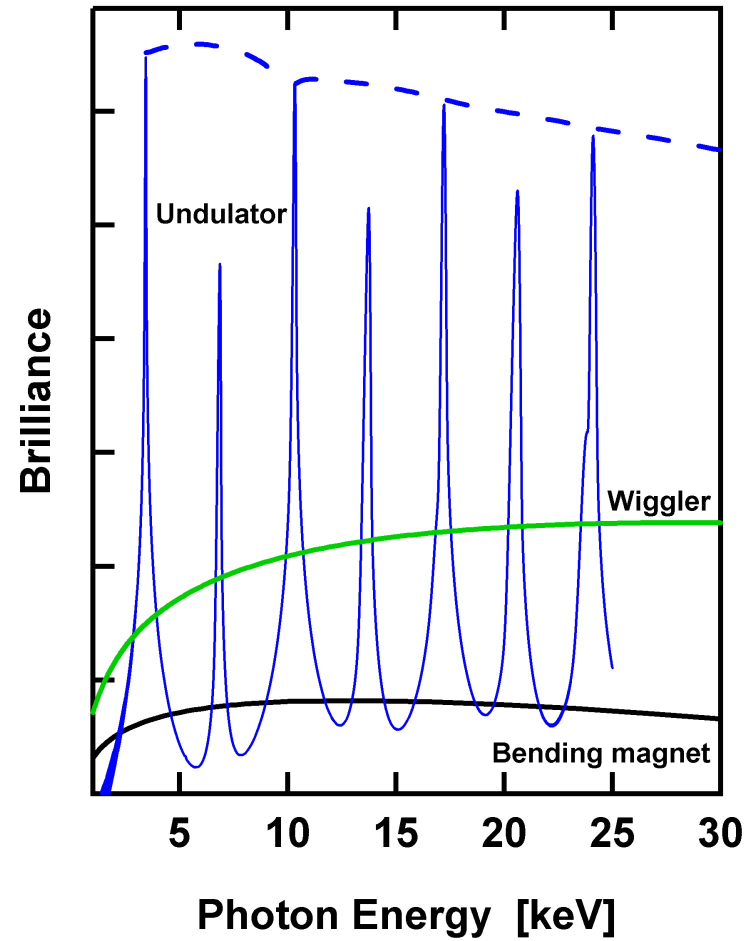
3. Synchrotron Light Sources

Image courtesy of ESRF

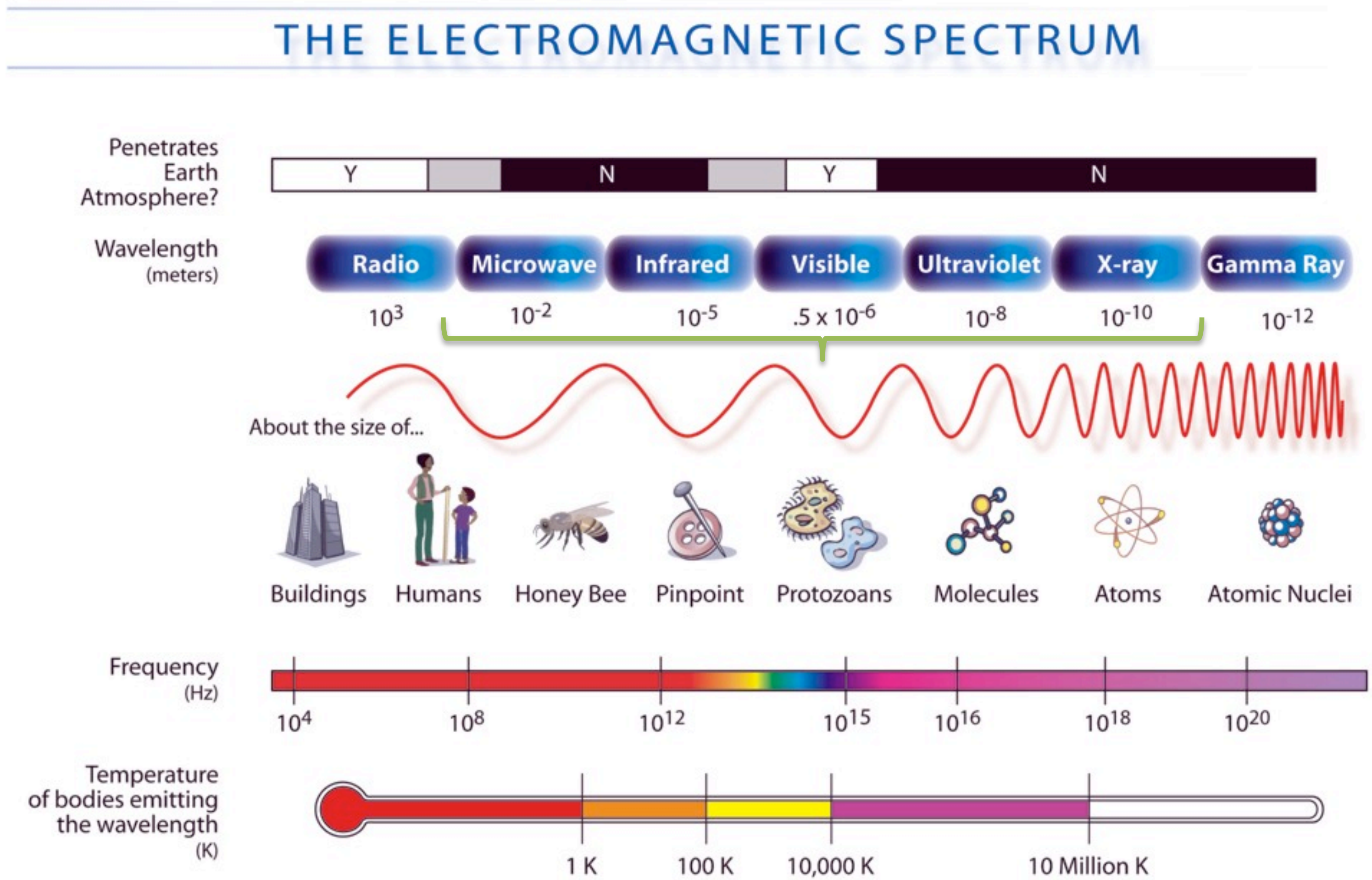
Synchrotron radiation is emitted by charged particles when accelerated radially







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



Synchrotron radiation: microwaves to hard x-rays (user can select)

High flux = quick experiments!

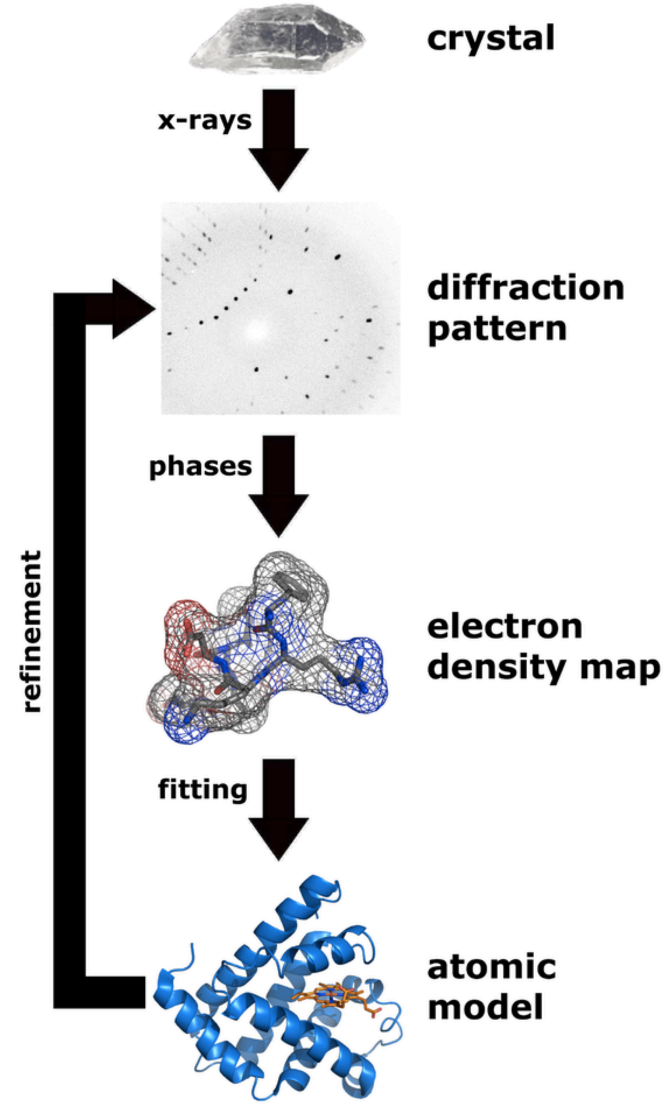
Pulsed structure = resolution of processes down to picoseconds

X-Ray crystallography

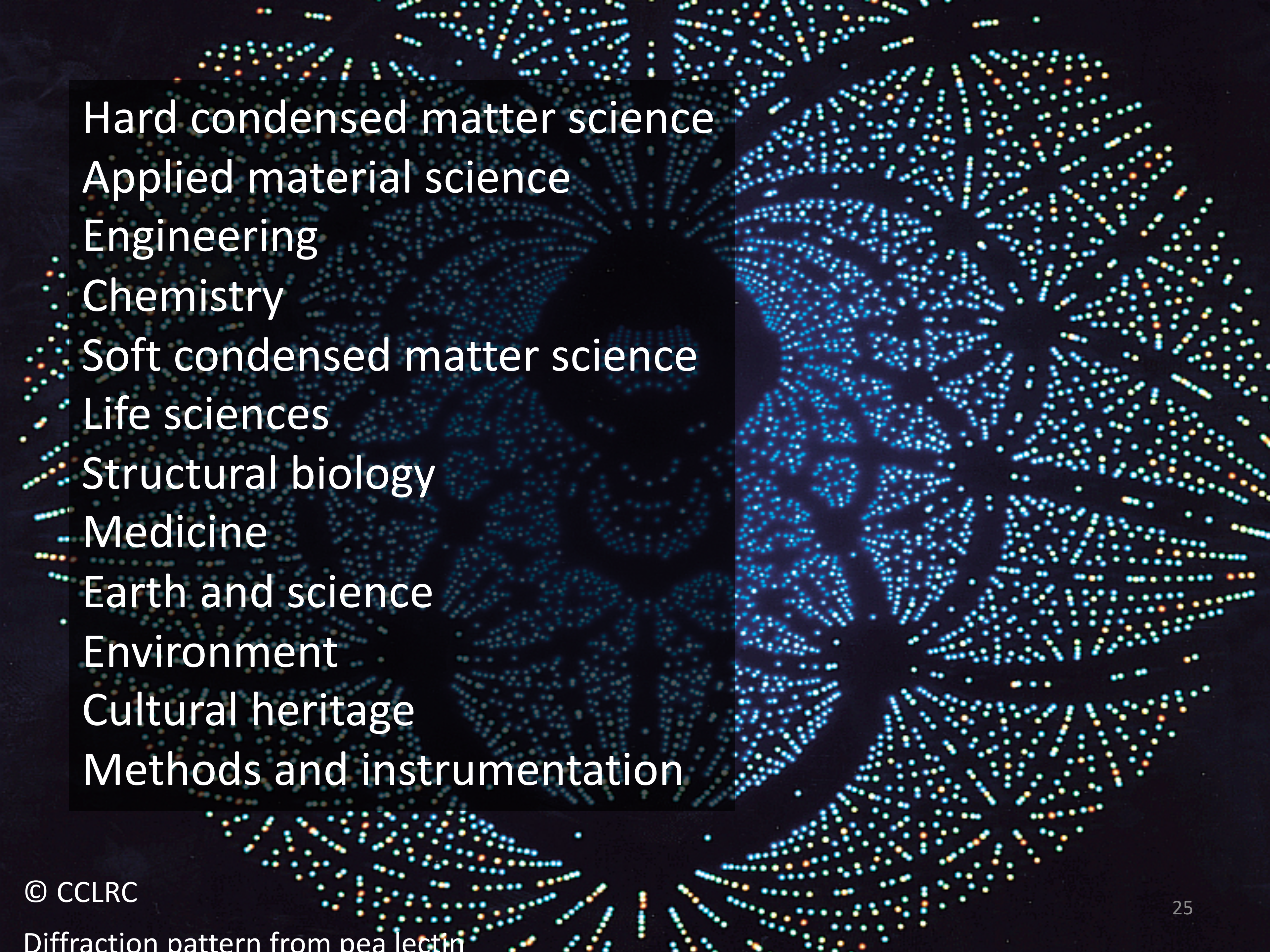
2014 was the International Year of Crystallography

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

The hardest part is forming the crystal…



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



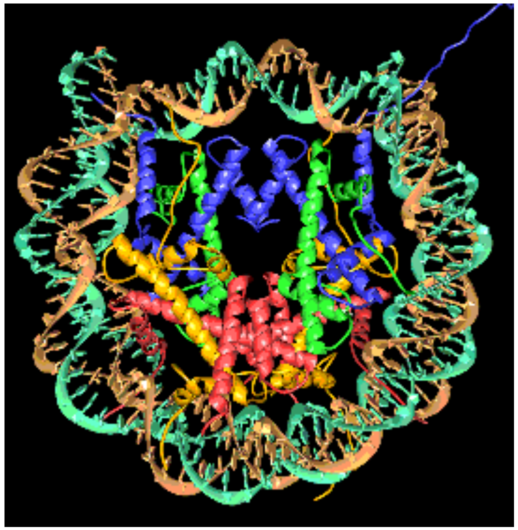
Hard condensed matter science
Applied material science
Engineering
Chemistry
Soft condensed matter science
Life sciences
Structural biology
Medicine
Earth and science
Environment
Cultural heritage
Methods and instrumentation

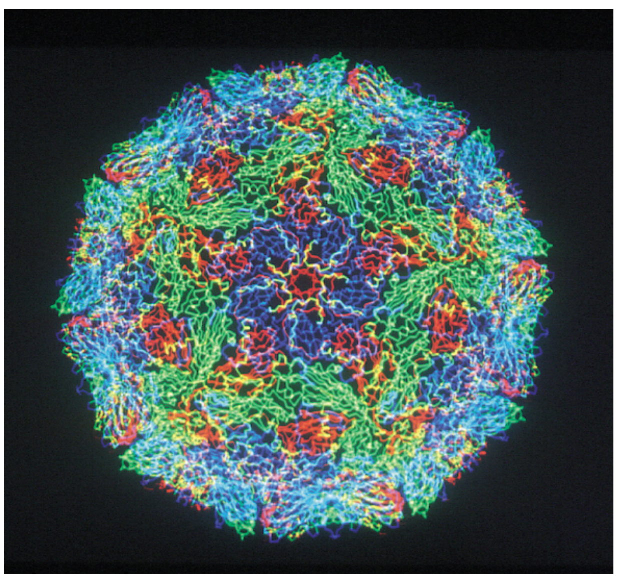
Diffraction pattern from pea lectin

Synchrotron Radiation Science

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.

Archeology/Heritage

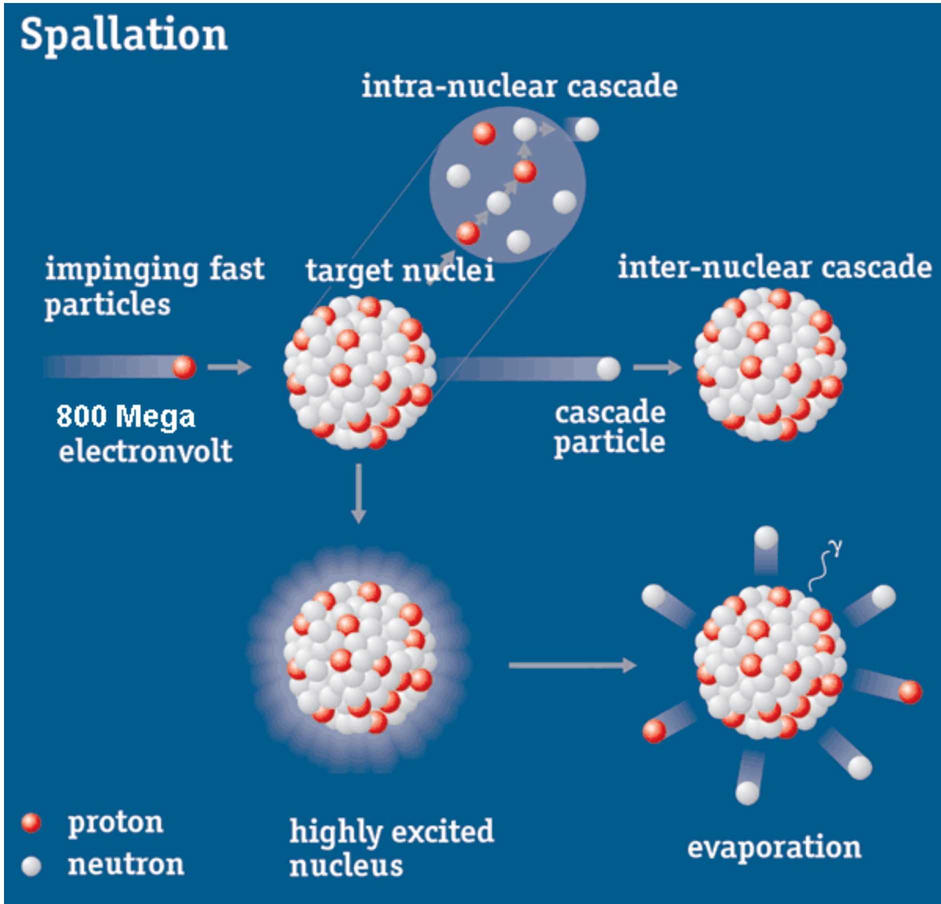
A synchrotron X-ray beam at the SSRL facility illuminated an obscured work erased, written over and even painted over of the ancient mathematical genius Archimedes, born 287 B.C. in Sicily.

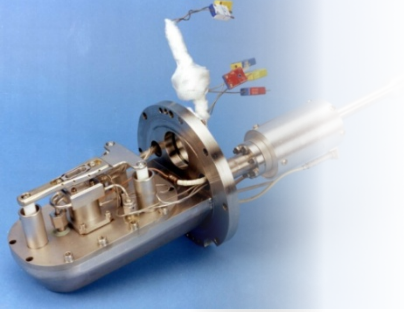
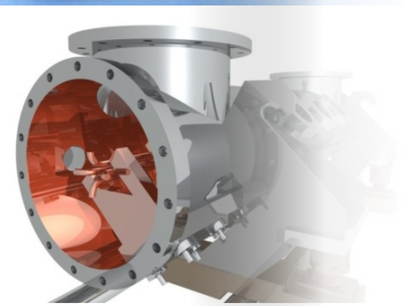
Using X-Ray induced fluorescence

4. Neutron Spallation Sources

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

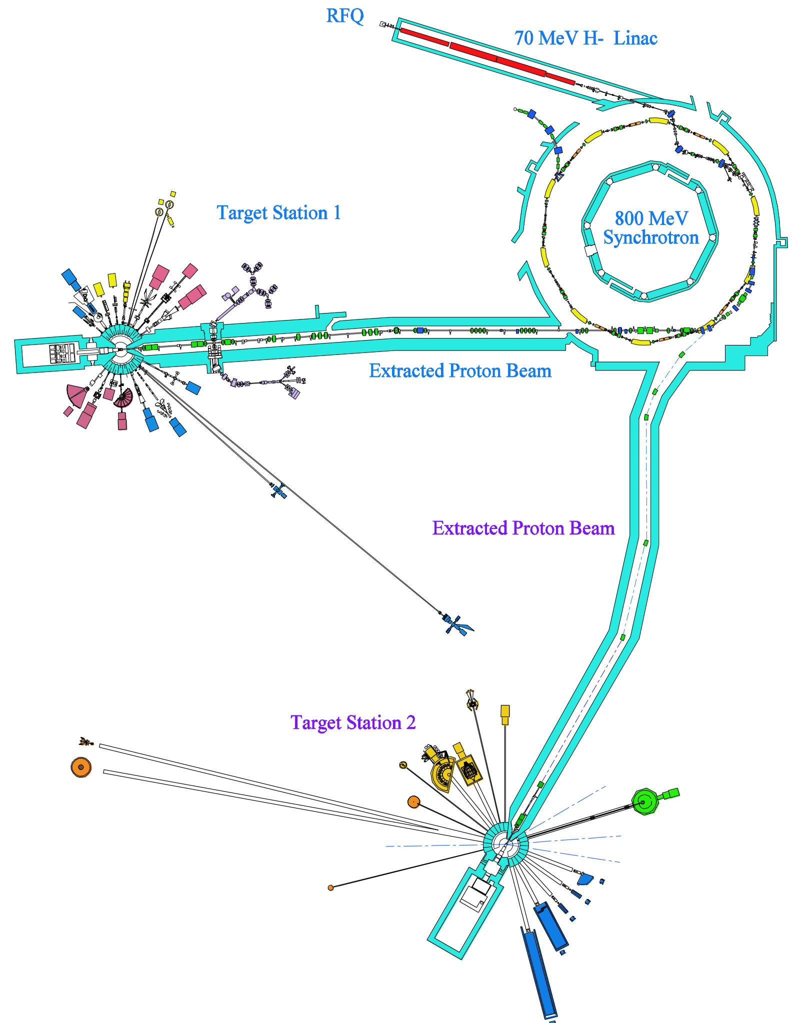
‘Neutrons tell you where atoms ***are*** and what atoms ***do***’




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)

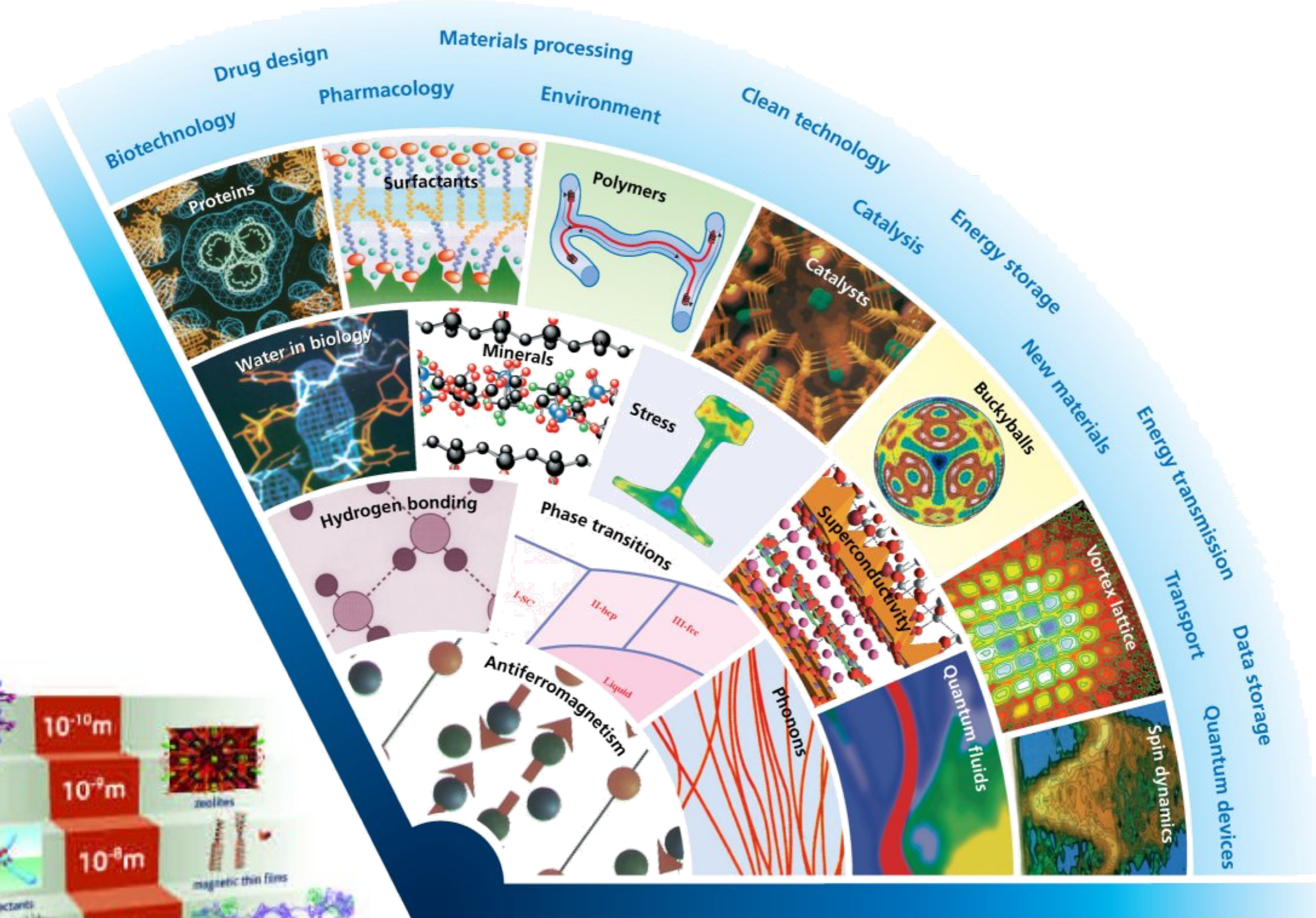
184 kW on target (148 kW to TS-1 at 40 pps, 36 kW to TS-2 at 10 pps).

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

Calculating beam power

- Power = Work/time $P = \frac{W}{T}$
- Work = force x distance $W = Fd$
- Force on particle in an electric field $F = qE$
- We know the electric field is (voltage/distance) and the protons (charge +1) have gained 800 MeV, so V=800MV.
- Also know current = charge/time

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



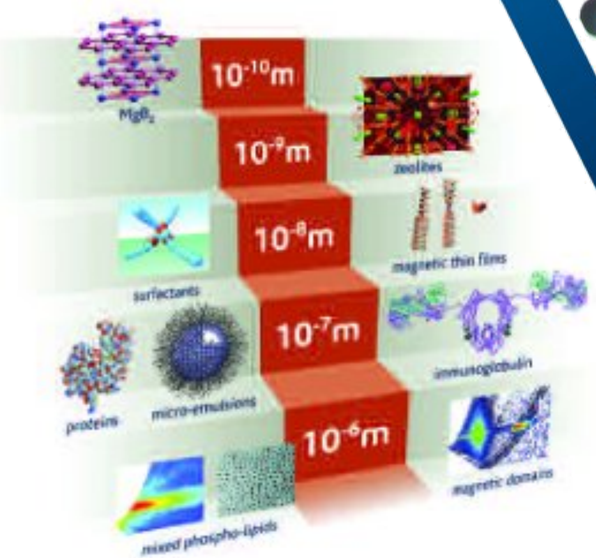
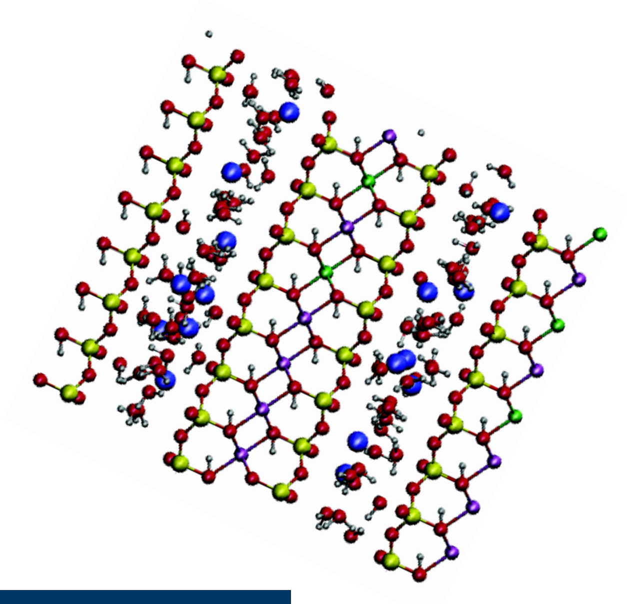


Image courtesy ISIS, STFC.

Unblocking oil pipes

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

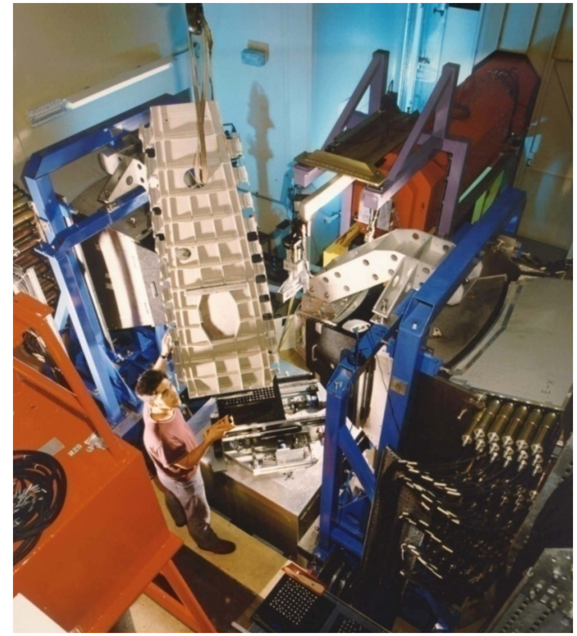


"ISIS allowed us to understand more clearly how asphaltenes aggregate, an important observation from a flow assurance point of view and should allow more efficient extraction of hydrocarbons in the future."

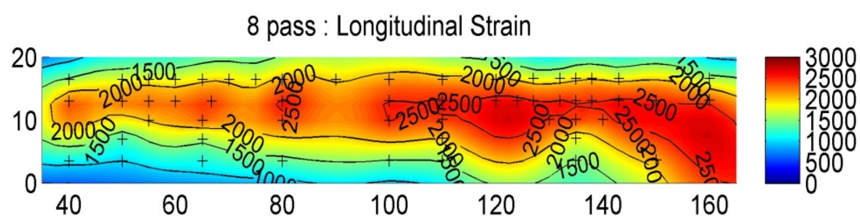
–Edo Boek, Schlumberger Cambridge Research, Senior Research Scientist

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



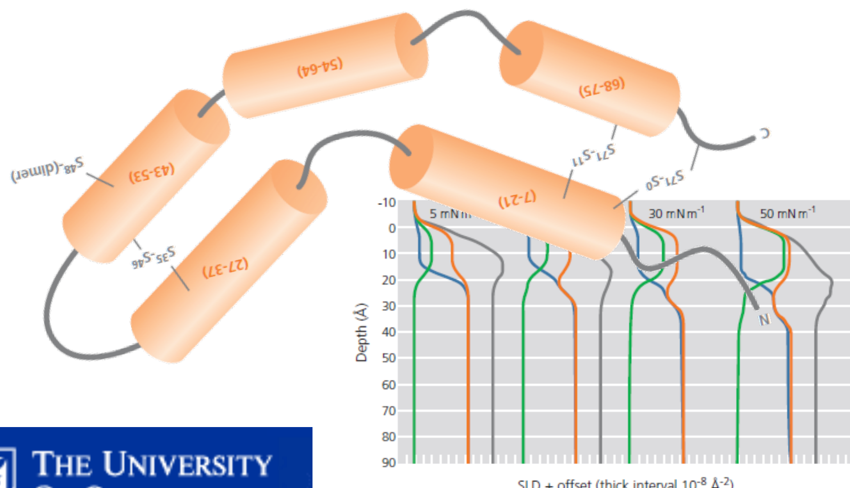
AIRBUS

"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



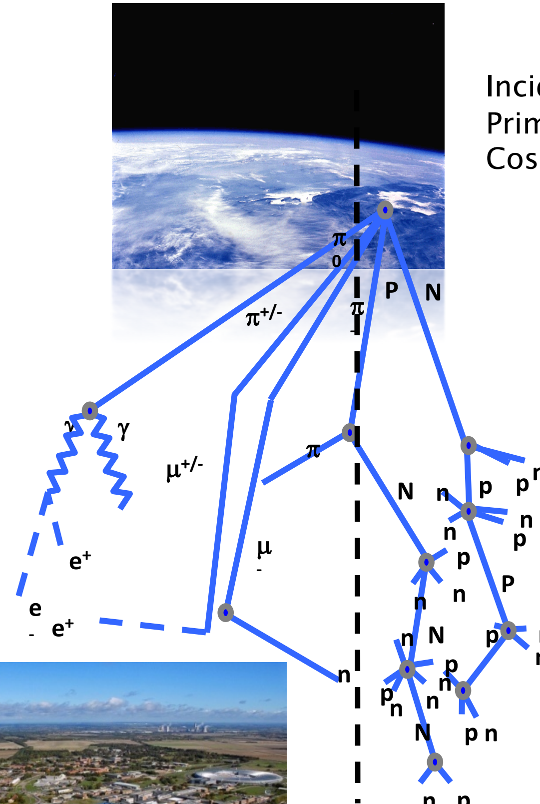
"ISIS is the premier place in the world to work with neutrons and liquid surfaces. In collaboration with the University of Queensland we were able to discover how proteins and phospholipids act together to enable lung function."

- Dr Stephen Holt, ISIS neutron scientist

The University of Queensland
Australia

Fast neutron testing for the semiconductor industry

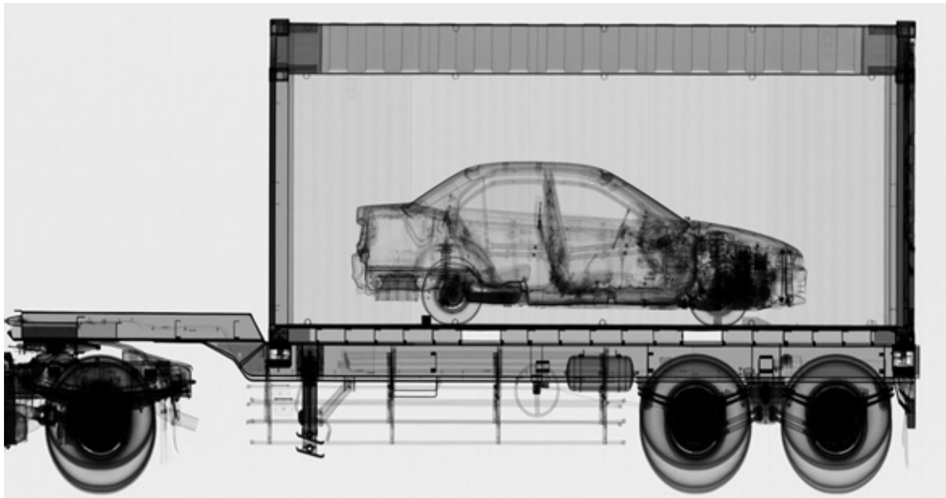
- **Atmospheric neutrons** collide with microchips and **upset microelectronic devices** every few seconds
- **300 x greater** effect at **high altitude**
- **ISIS enables manufacturers to mitigate against the problem** of cosmic radiation
- **Increased confidence** in the quality and safety of aerospace electronic systems



"ISIS is one of few facilities in the world capable of producing enough very high energy neutrons to perform accelerated testing."
–Andrew Chugg, MBDA, SEEDER consortium

5. Energy and Security Applications

Cargo scanning



Cargo containers scanned at ports and border crossings

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

Container must be scanned in 30 seconds.

Image source: Varian medical systems

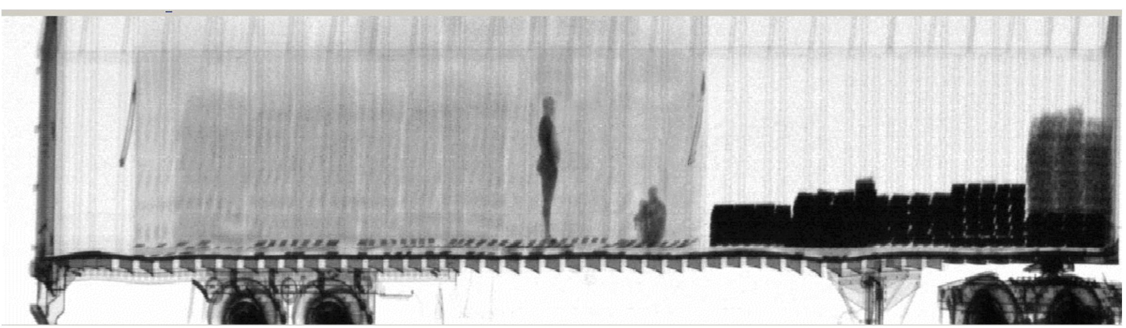


Image: dutch.euro

Materials testing for fusion

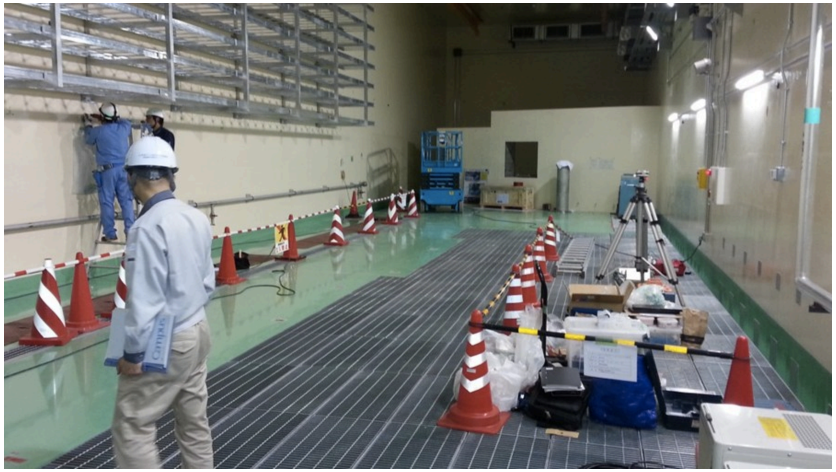
Source: IFMIF.org

“deuterium-tritium nuclear fusion reactions will generate neutron fluxes in the order of 10^{18} $m^{-2}s^{-1}$ 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

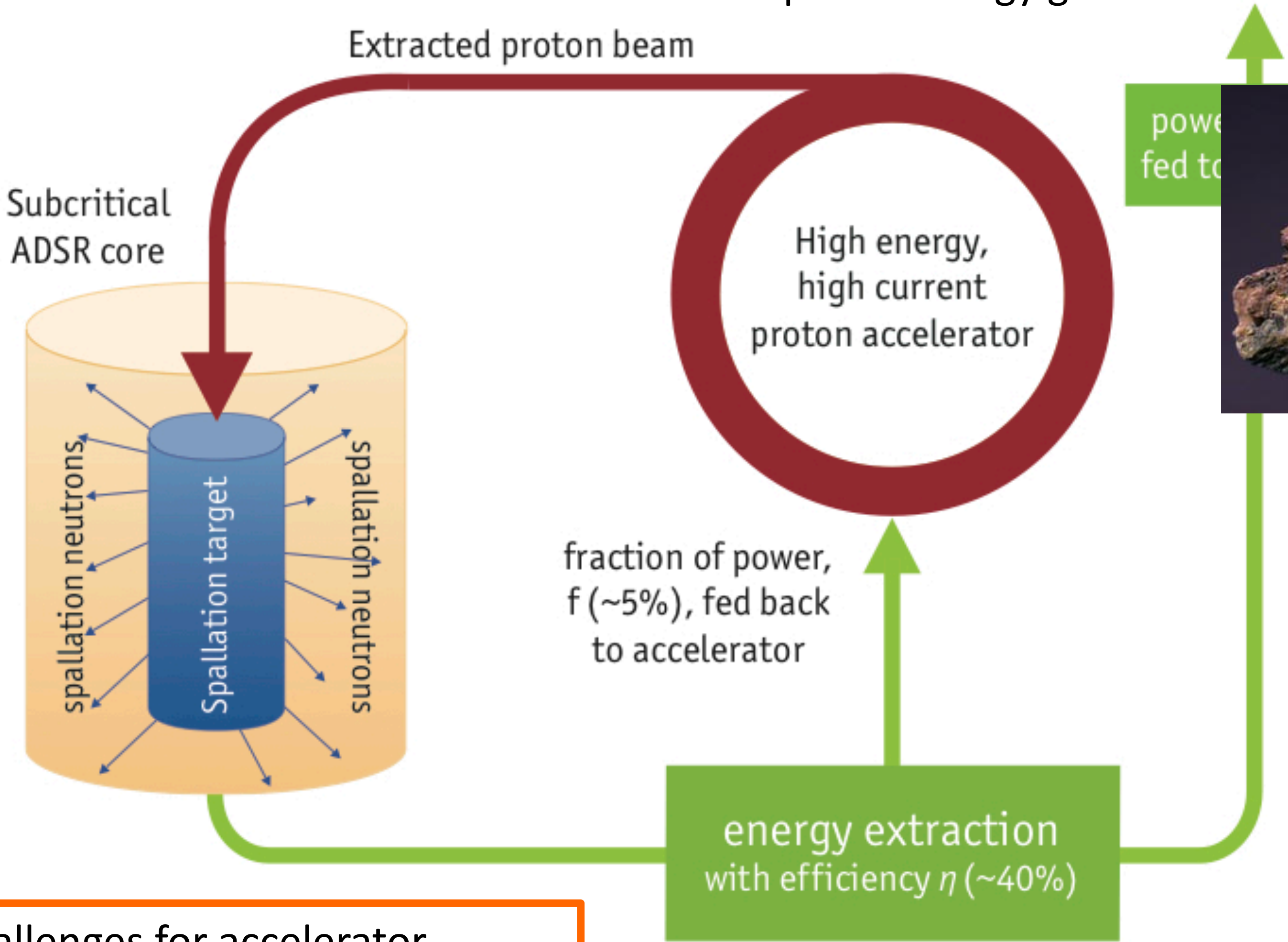
To de-risk IFMIF, first a test accelerator ‘LIPAc’ is being built



Installation of ‘LIPAc’ test accelerator has started in Japan

Accelerator Driven Systems

Transmutation of nuclear waste isotopes or energy generation

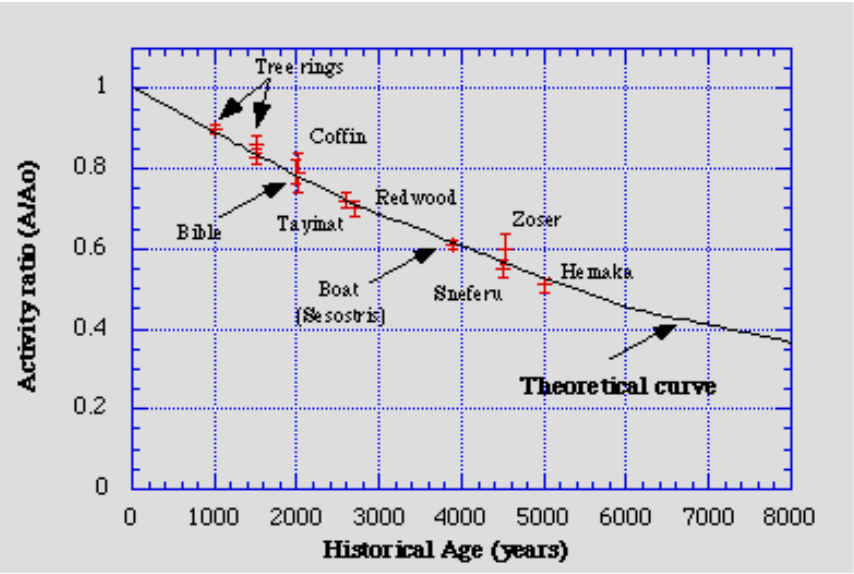


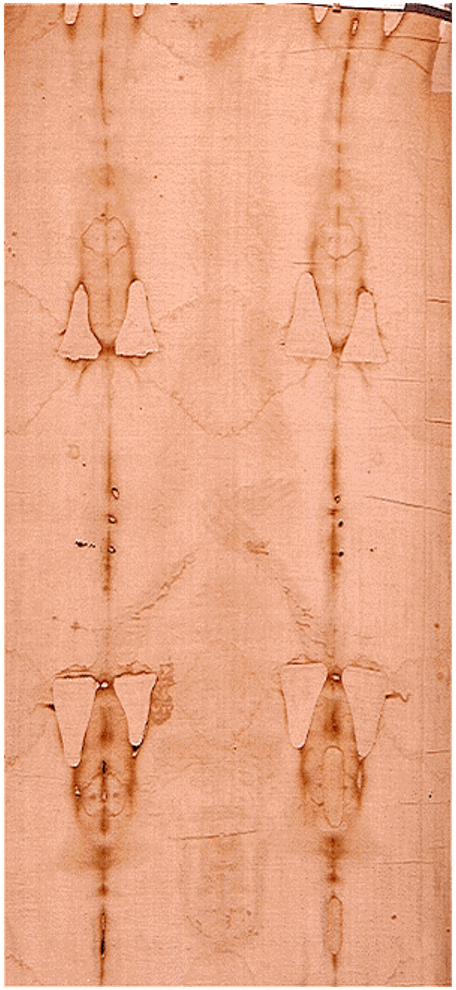
Thorium

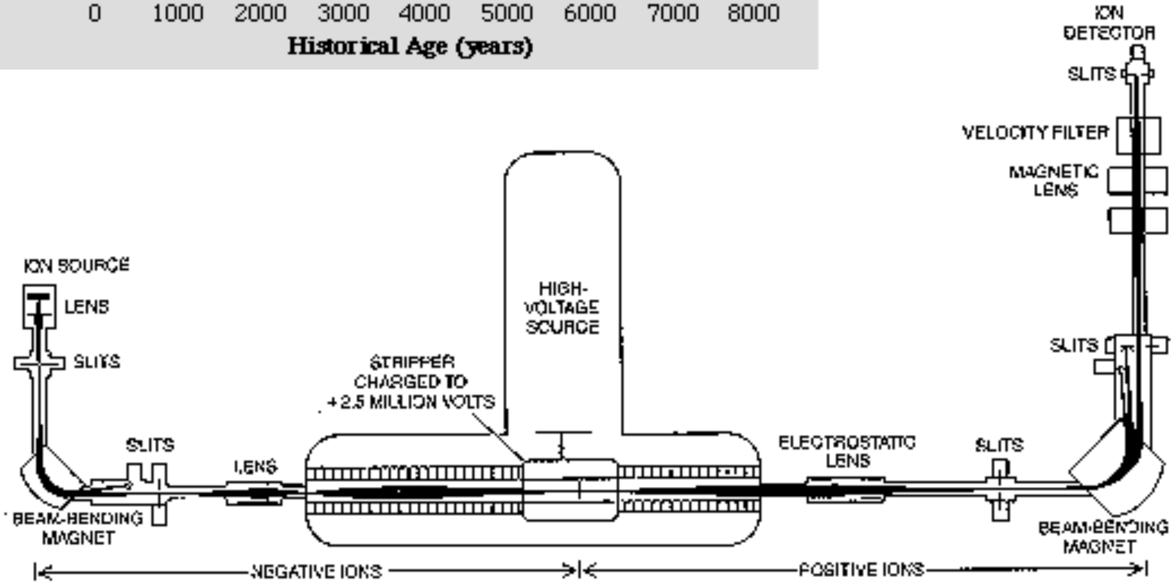
Major challenges for accelerator technology in terms of beam power (>10MW) and reliability

6. Historical and cultural applications

Radiocarbon Dating





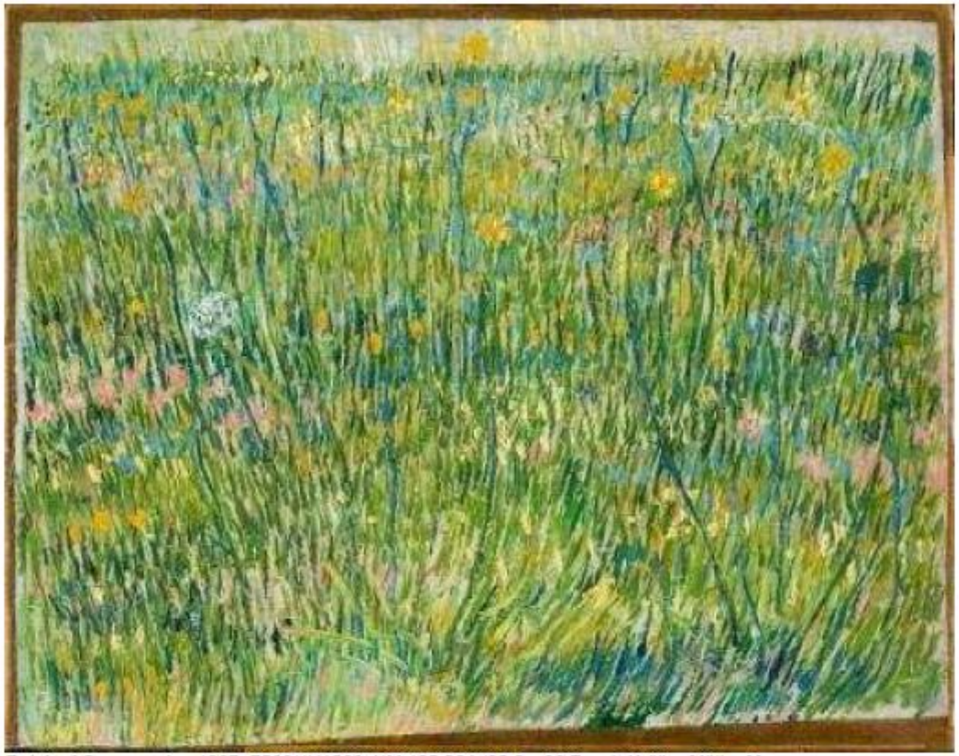


For more accuracy, isolate C-14 from other isotopes
“AMS” = Accelerator Mass Spectrometry

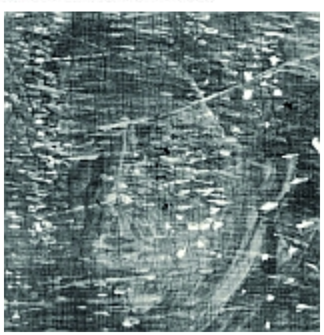
Accelerators can study art

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

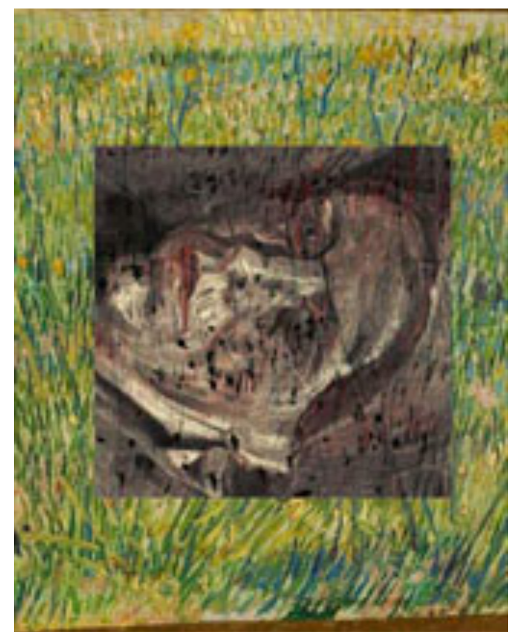
Used X-ray fluorescence technique
Distribution of Hg and Sb pigment allowed a reconstruction of underlying image



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



It showed a portrait of a woman underneath

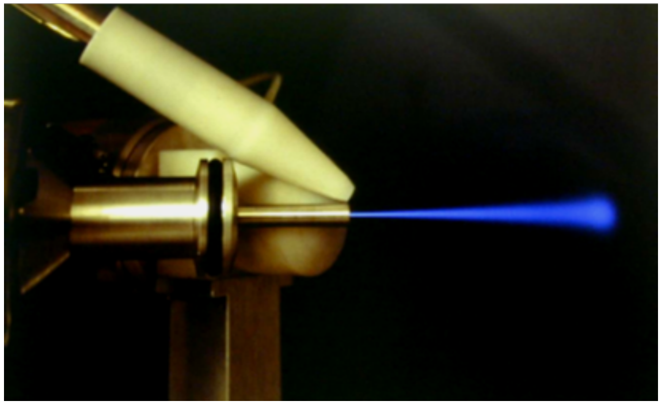


http://www.javno.com/en-bestseller/van-gogh-first-victim-of-particle-bombarding_185316

Accelerators can help spot art forgeries

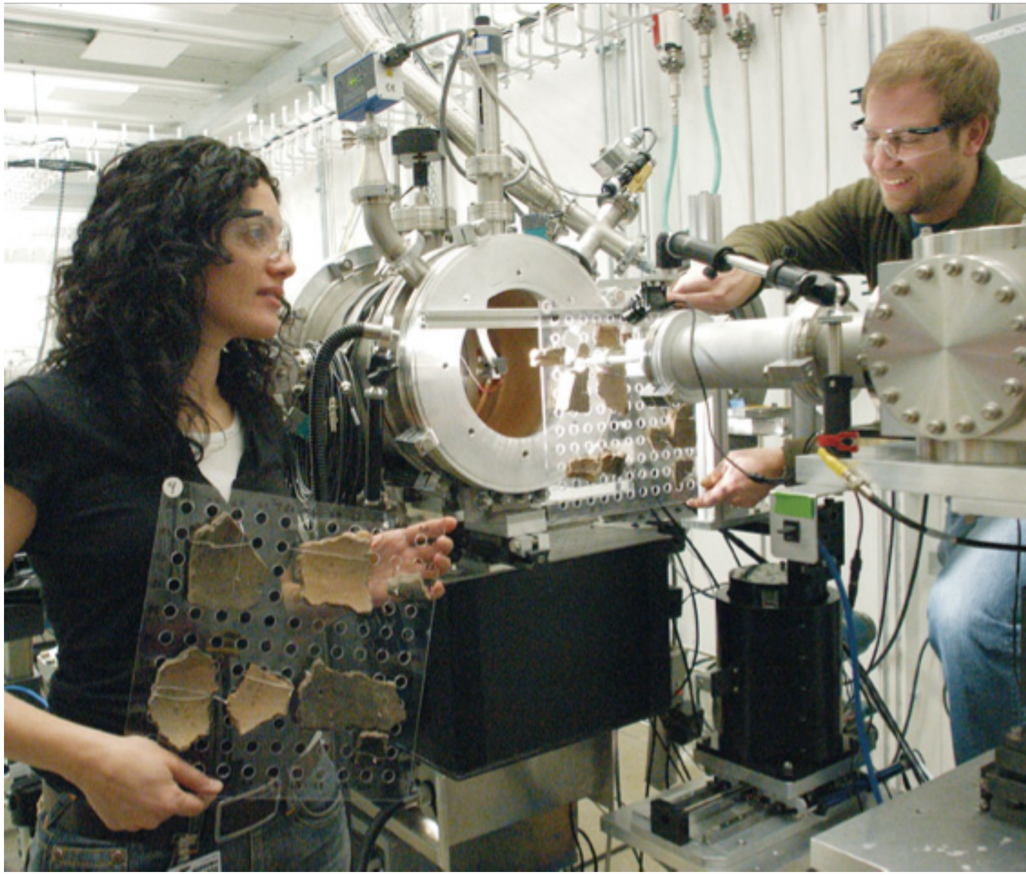
Ion Beam Analysis shows us the chemical composition of pigments used in paint

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



Accelerators in archaeology

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

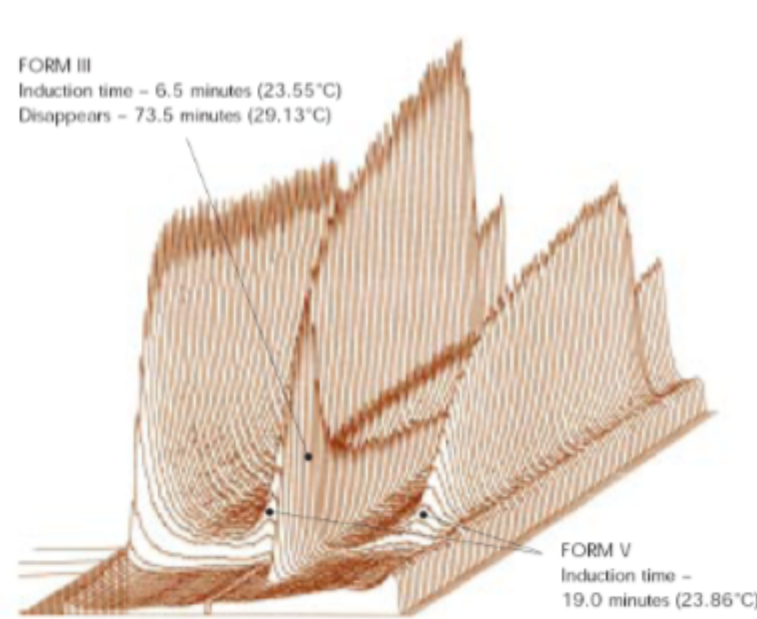


Pottery from Armenia, dating back to 1300 BC,
is set up for a synchrotron experiment

Image: Argonne National Laboratory

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

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 Emai

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.

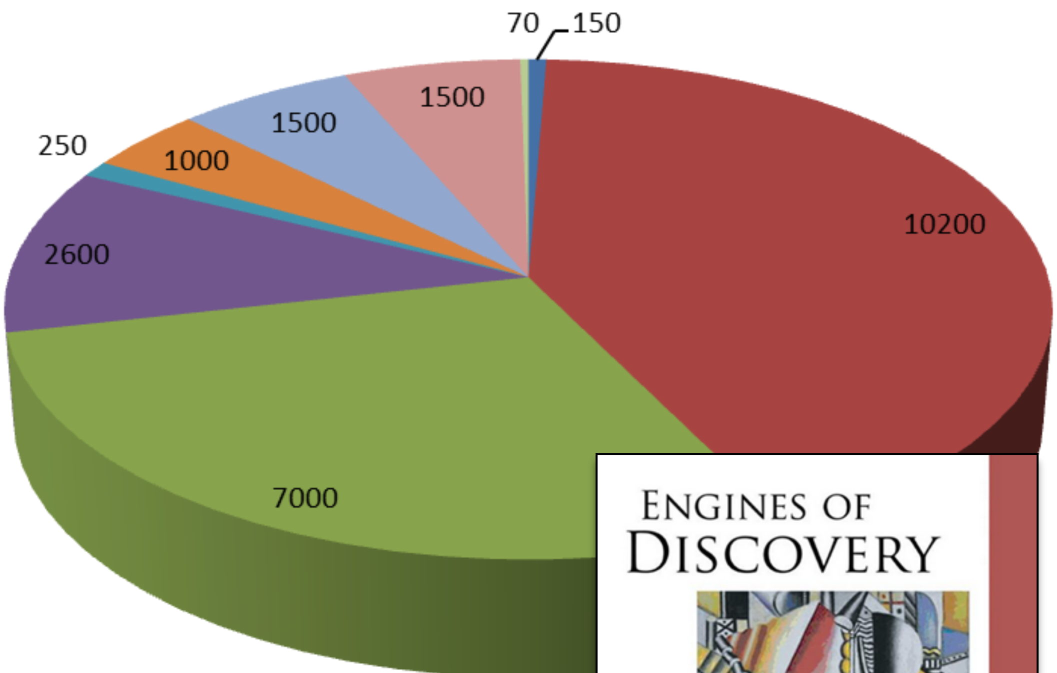
Next time someone asks you what accelerators are for…

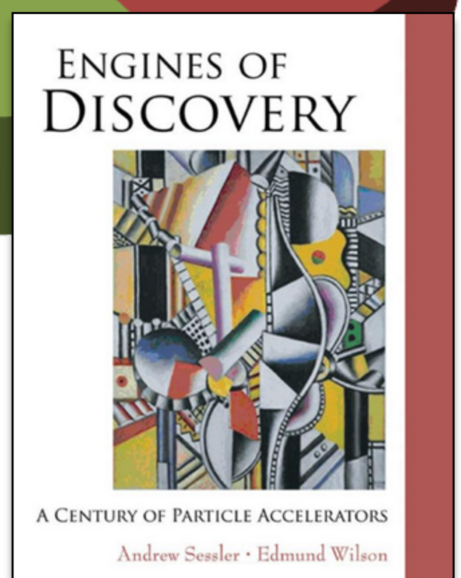
"A beam of the right particles with the right energy at the right intensity can shrink a tumor, produce cleaner energy, spot suspicious cargo, make a better radial tire, clean up dirty drinking water, map a protein, study a nuclear explosion, design a new drug, make a heat-resistant automotive cable, 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

Accelerators in the world >24000





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

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