Applications of Accelerators

CERN Introductory Accelerator School
Prague, September 2014

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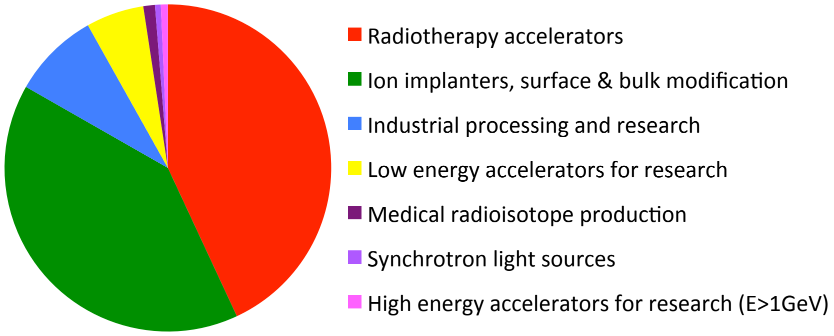
STFC Rutherford Appleton Laboratory, UK

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

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



~30,000 accelerators in the world
(not including CRT televisions…)

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

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1. Medical Applications

Radiopharmaceuticals
Isotope production for PET scans
X-ray radiotherapy
Proton and ion therapy
Equipment sterilisation
+others

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**	

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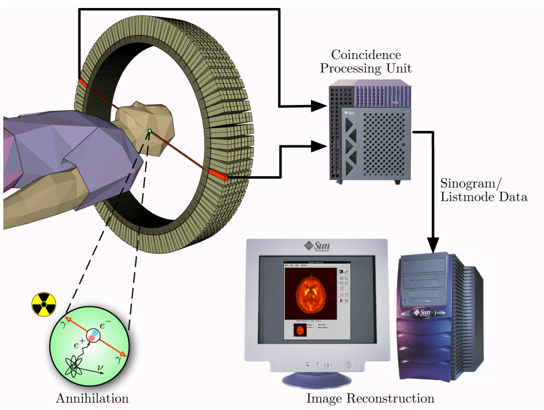
Radioisotope production

- 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

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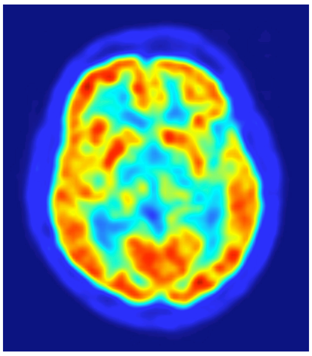

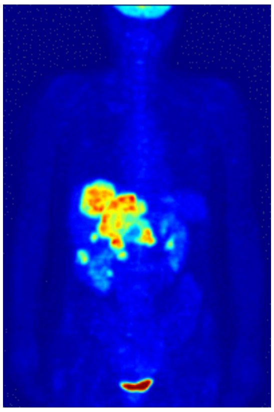

- Fluorodeoxyglucose or FDG carries the F18 to areas of high metabolic activity
- 90% of PET scans are in clinical oncology

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X-ray radiotherapy

Linac

Foil to produce x-rays

Collimation system

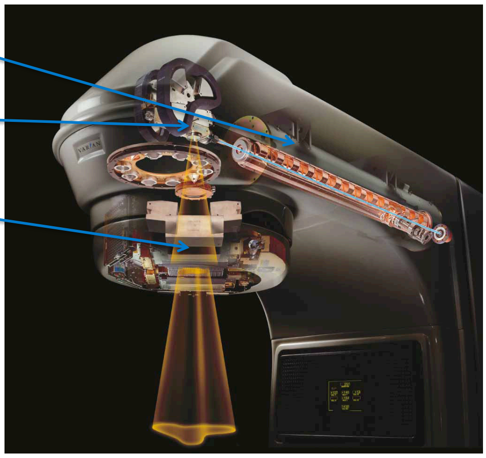

Image: copyright Varian medical systems

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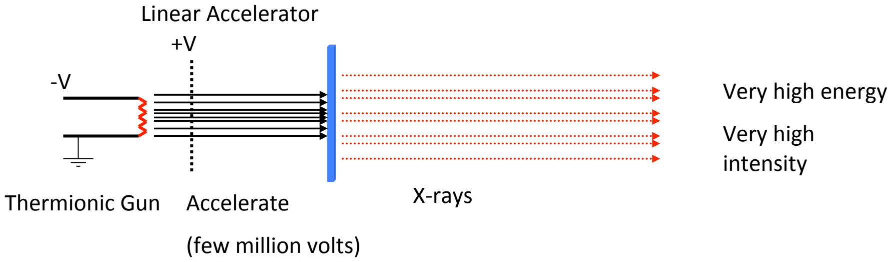
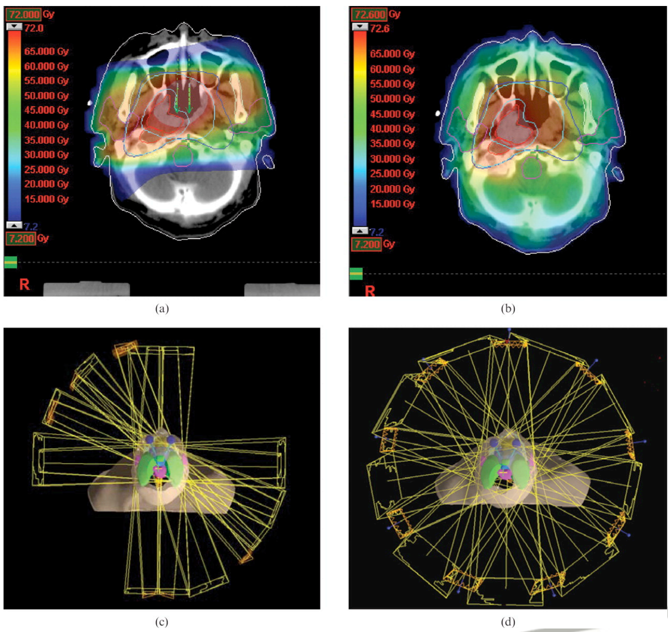
X-ray radiotherapy



X-ray radiotherapy source



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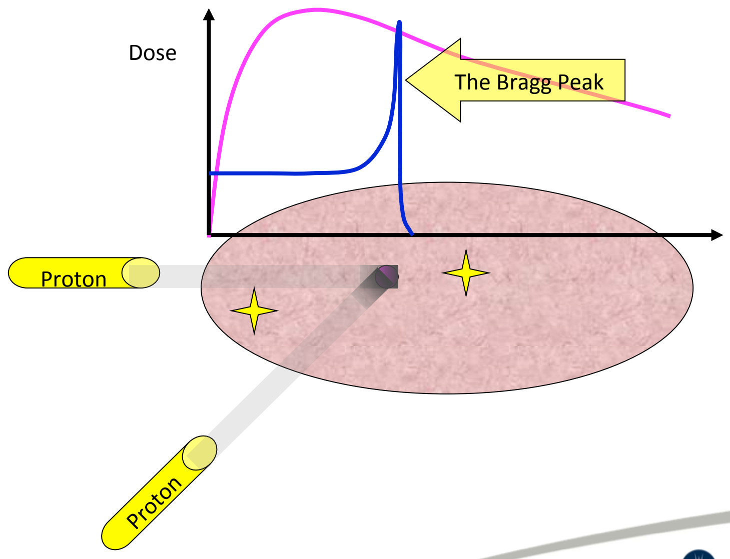
Can we only use X-rays?



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Energy loss in materials

The relativistic version of the formula reads:

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

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

where

- 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

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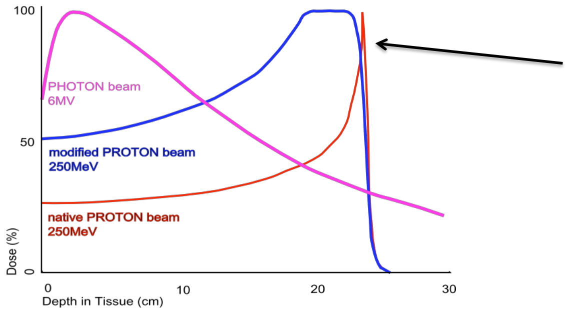
Charged Particle Therapy



Bragg Peak

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

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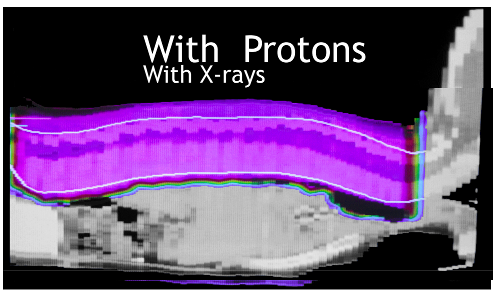
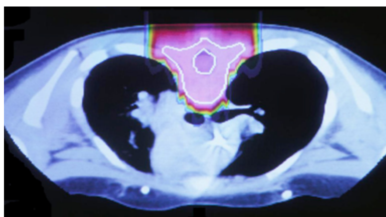
Proton therapy

"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





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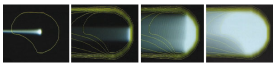
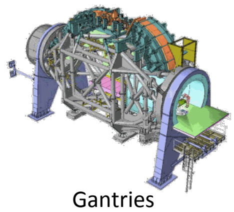
A few developments

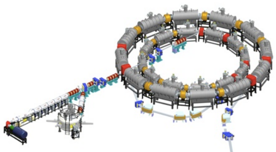


Spot Scanning

Proton Radiography

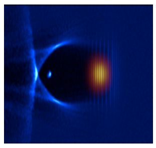


Gantries



FFAG Accelerators

Dielectric Wall Accelerators



Laser Plasma Accelerators

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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 sterlisation 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

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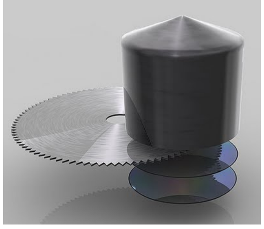
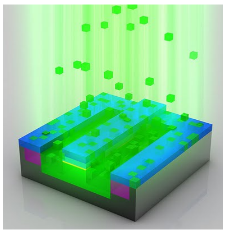
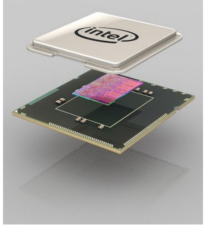
2. Industrial accelerators

Ion implantation
Electron beam processing
Food irradiation
Other uses

Ion implantation







Images courtesy of Intel

Electrostatic accelerators are used to deposit ions in semiconductors.

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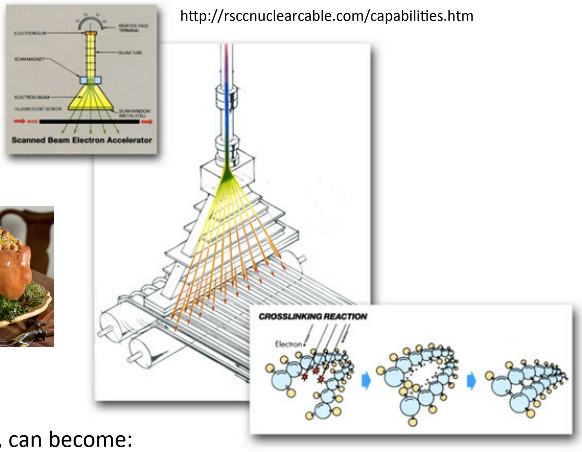
Electron beam processing

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

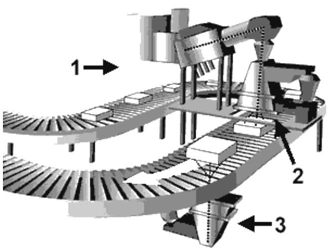
http://rsccnuclearcable.com/capabilities.htm



When polymers are cross-linked, can become:

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

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

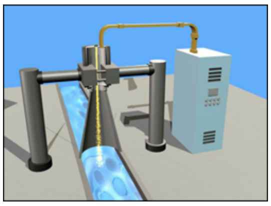
Foods authorised for irradiation in the EU:

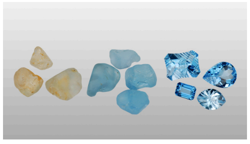
Lower dose → Higher dose

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





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

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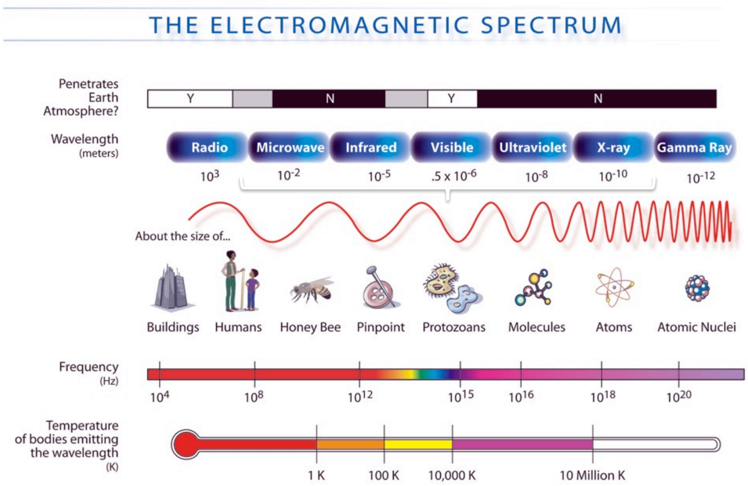
3. Synchrotron Light Sources



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

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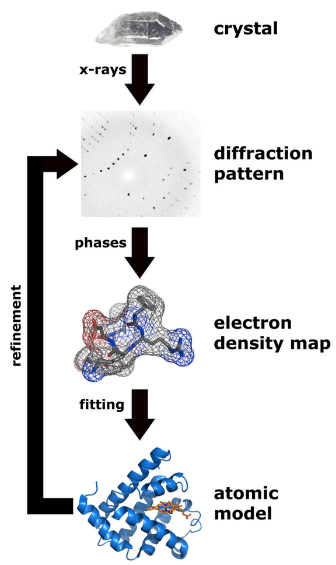
X-Ray crystallography

2014 is 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

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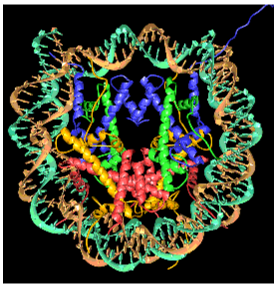
Synchrotron Radiation Science

Biology

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



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

Medicine, Biology, Chemistry, Material Science, Environmental Science and more

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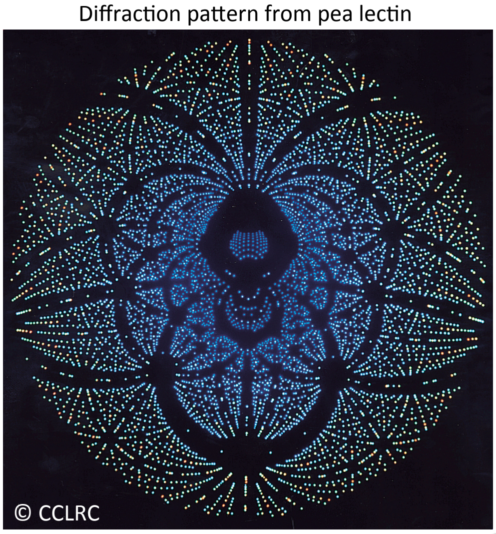
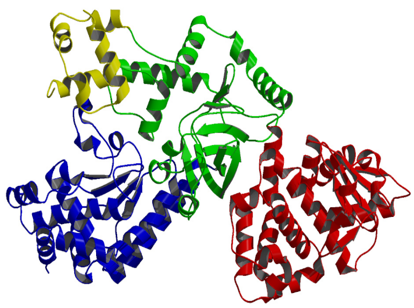
Synchrotron Radiation Science

Diffraction pattern from pea lectin



© CCLRC

Structure of Anthrax



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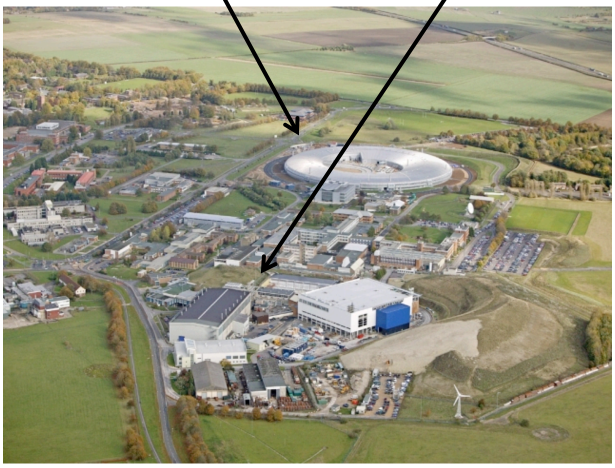
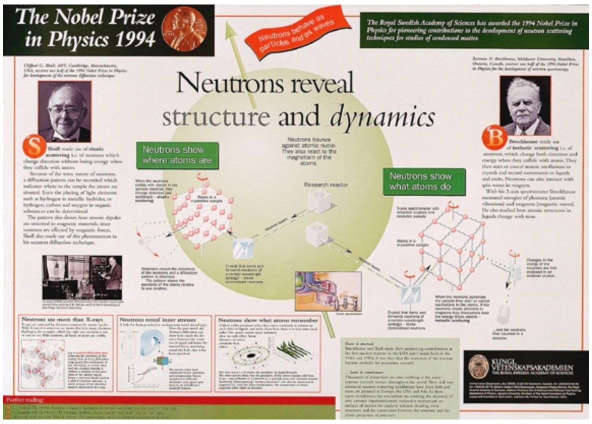
Diamond & ISIS



4. Neutron Spallation Sources

Why Neutrons?



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

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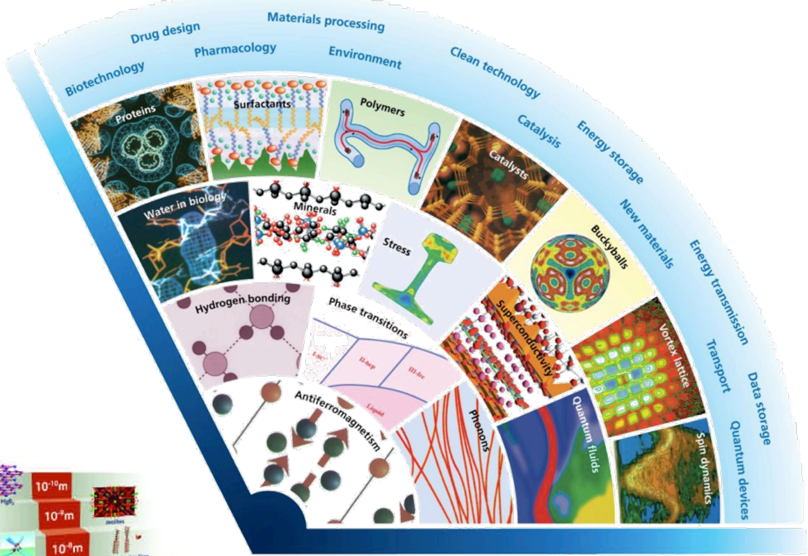

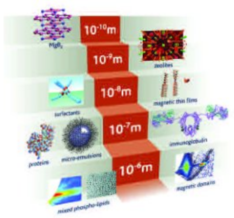

Image courtesy ISIS, STFC.

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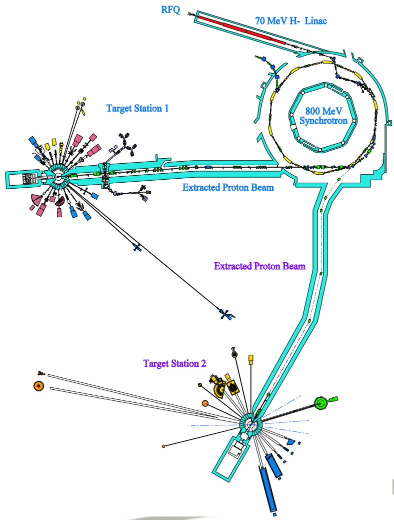
ISIS Accelerators and Targets

- 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).



Calculating beam power

Power = Work/time $$P = \frac{W}{T}$$

Work = force x distance $$W = Fd$$

Force on particle in an electric field $$F = qE$$

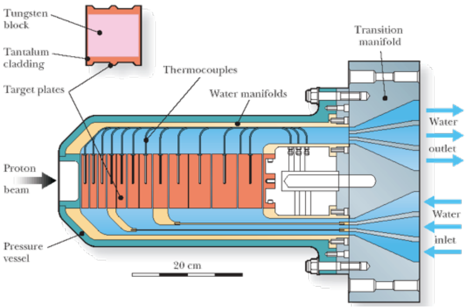
We know the electric field is (voltage/distance) and the protons (charge +1) have gained 800 MeV, so V=800MV.

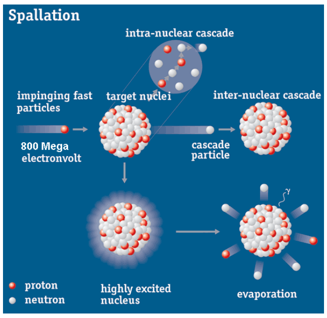
Also know current = charge/time

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

Spallation Target (TS-1)

- ≈ 2.3×10^{13} (4 μC) ppp on to TS-1 tantalum coated tungsten target (40 pps)
- ≈15–20 neutrons/proton, ≈ 4×10^{14} neutrons/pulse
- Primary neutrons from spallation: evaporation spectrum (E ≈ 1 MeV) + high energy tail





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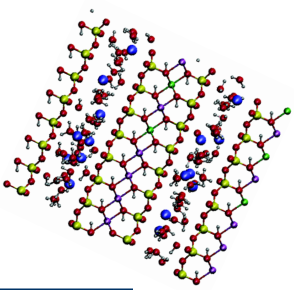
Unblocking oil pipes

- **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

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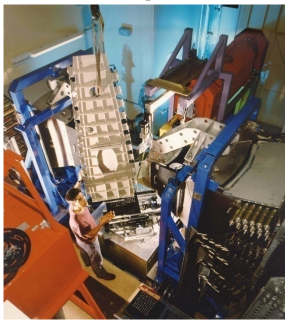
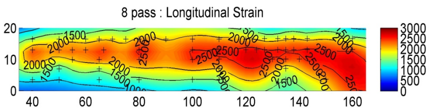
Stresses in Airbus A380 Wing

- **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

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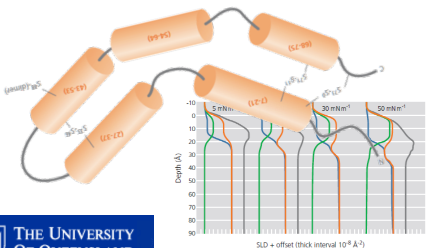
Understanding infant lung structure

- 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



The University Of Queensland Australia

"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

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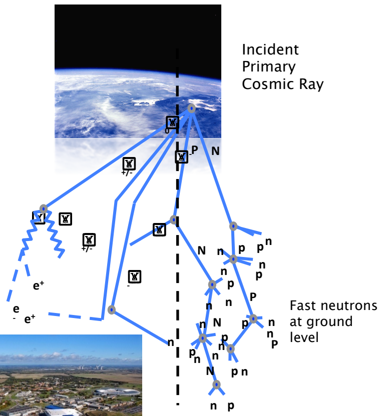
Fast neutron testing for the semiconductor industry

- **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

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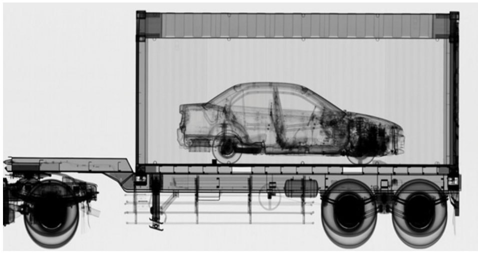
5. Energy and Security Applications

Cargo scanning

Materials testing for fusion

Accelerator driven subcritical reactor (ADSR)

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

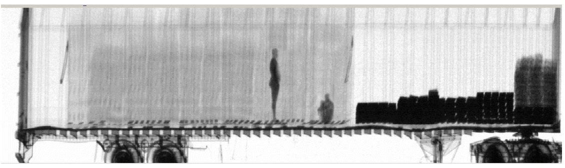


Image: dutch.euro

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Materials testing for fusion

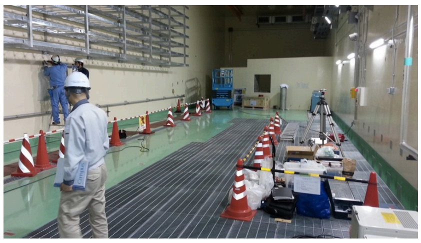
Source: IFMIF.org

"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

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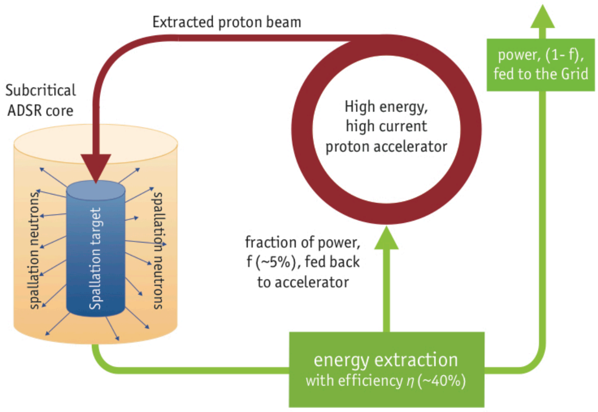
ADS systems

Transmutation of nuclear waste isotopes or energy generation



Thorium

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

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6. Historical and cultural applications

Radiocarbon dating

Fraud prevention

Radiocarbon (^{14}C) formation and decay

-formed by interaction of cosmic ray spallation products with stable N gas

$$ {}^{1}_{0}n + {}^{14}_{7}N \rightarrow {}^{14}_{6}C + {}^{1}_{1}H $$

-radiocarbon subsequently decays by β^- decay back to ^{14}N with a half-life of 5730y

$$ {}^{14}_{6}C \rightarrow {}^{14}_{7}N + \beta^- + \bar{\nu} + Q $$

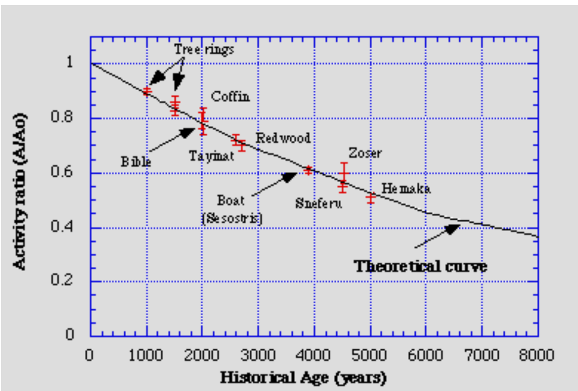
Radiocarbon dating was first explored by W.R. Libby (1946), who later won the Nobel Prize.

The activity of radiocarbon in the atmosphere represents a balance of its production, its decay, and its uptake by the biosphere, weathering, etc.

Which of these three things might change through time, and why?

Radiocarbon Dating

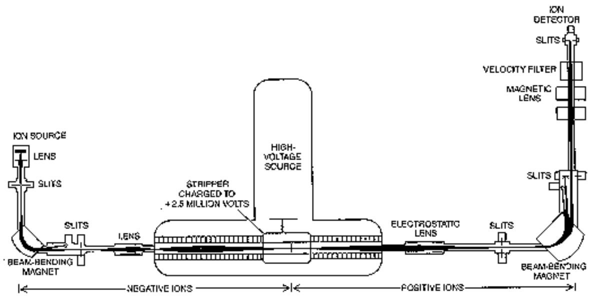
1) As plants uptake C through photosynthesis, they take on the ^{14}C activity of the atmosphere.
2) Anything that derives from this C will also have atmospheric ^{14}C activity (including you and I).
3) If something stops actively exchanging C (it dies, is buried, etc), that ^{14}C begins to decay.

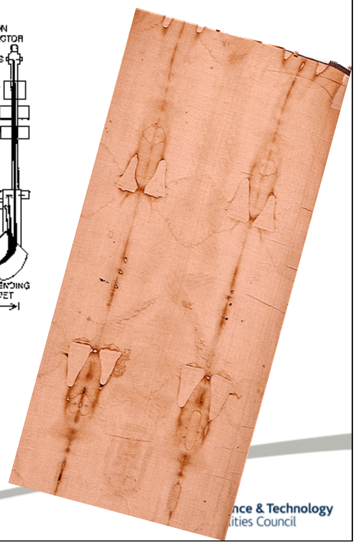


$$ A = A_0 e^{-\lambda t} $$

where present-day, pre-bomb, ^{14}C activity = 13.56dpm/g C

Mass Spectrometry





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

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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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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."