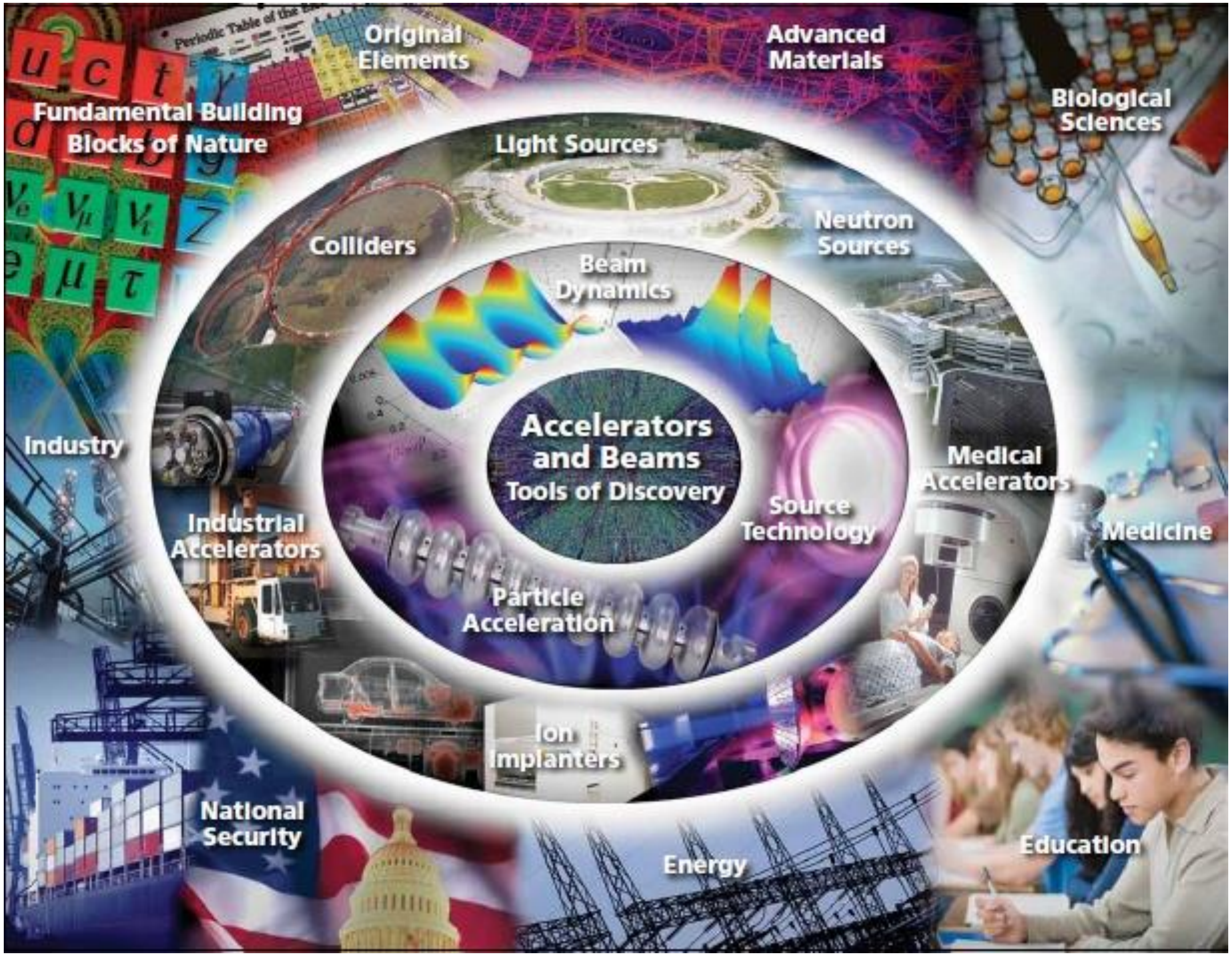
Lecture 2
Applications of Accelerators

Professor Emmanuel Tsesmelis
Principal Physicist, CERN
Visiting Professor, University of Oxford

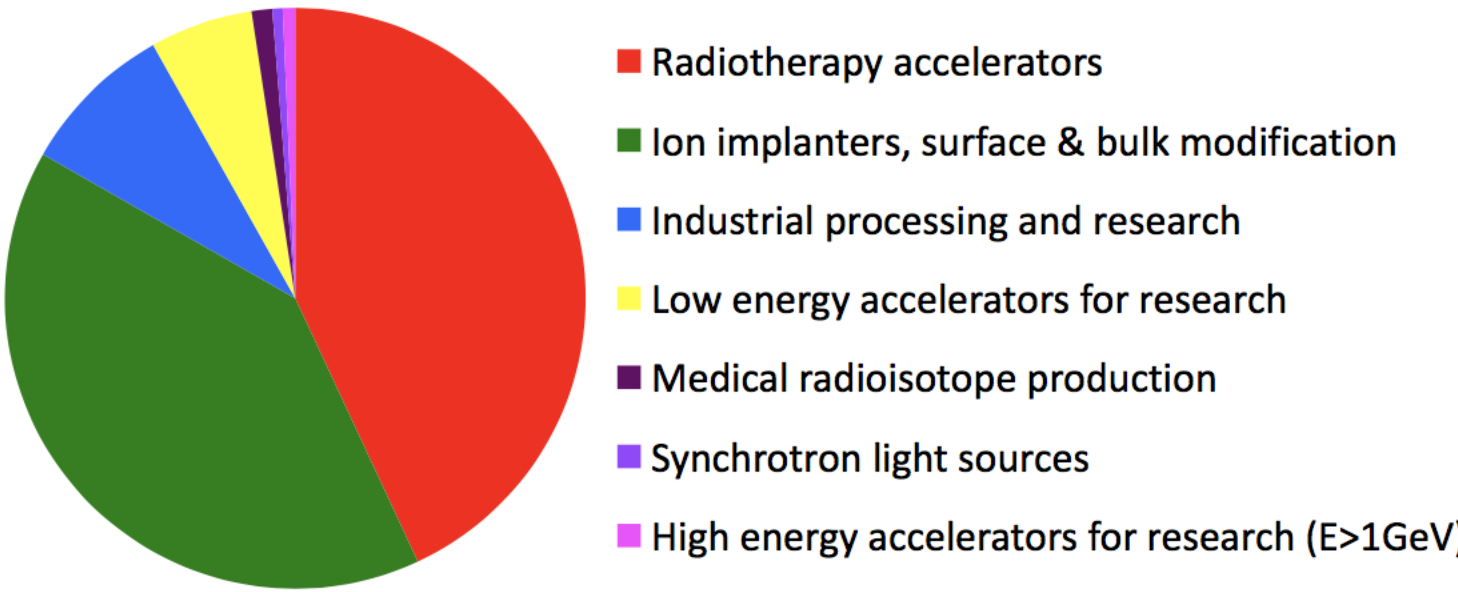
Graduate Accelerator Physics Course
John Adams Institute for Accelerator Science
11 October 2023

Introduction



Accelerators Worldwide

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

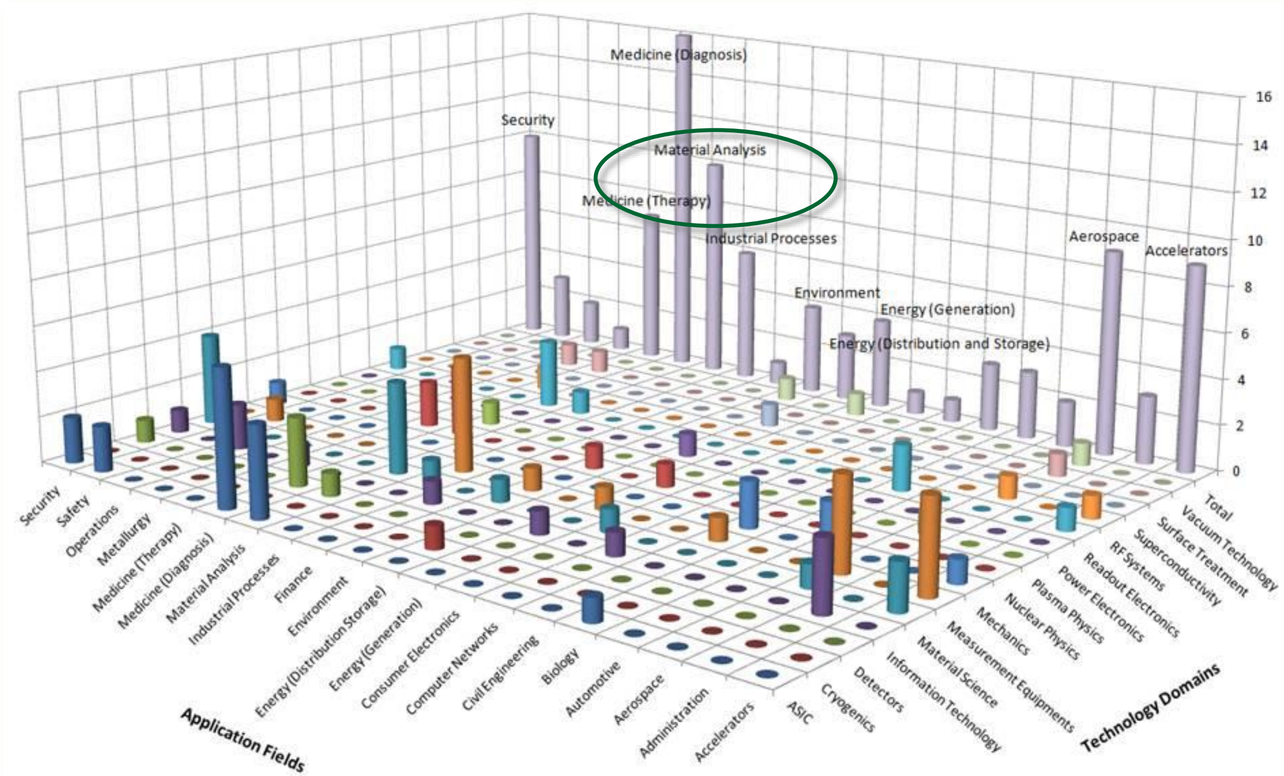


There are roughly 35,000 accelerators in the world
(Above 1 MeV…)

Accelerators are not only for particle physics

Accelerator Technologies and Innovation

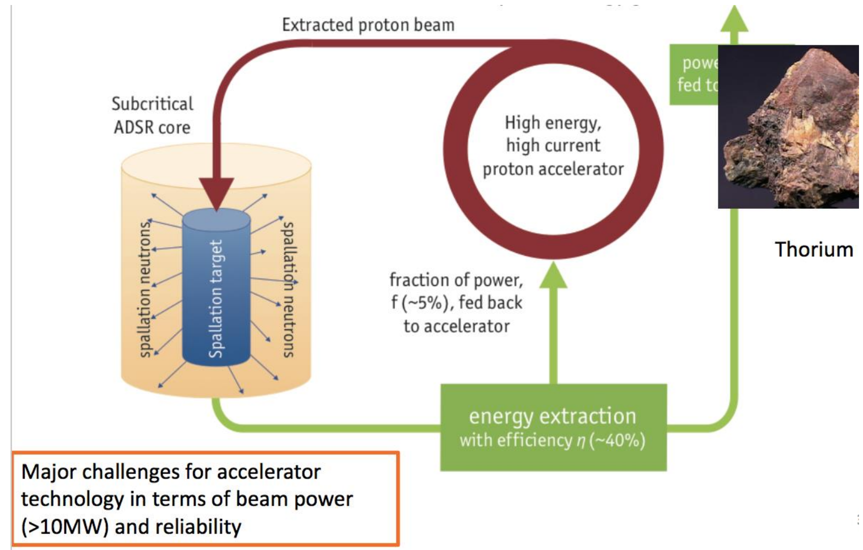
Cutting edge Research Infrastructures play a key role in a knowledge driven society



Knowledge is – and will be more and more –
the most precious resource for a sustainable development

Accelerators for Energy

- Accelerator-Driven Subcritical System
  - External source of neutrons to drive sub-critical reactor loaded with non-fissile fuel such as ^{232}Th.
  - Neutrons produced by high-power proton beam through spallation, breeding ^{233}U causing it to fission.
  - Cannot support self-sustaining chain reaction.
  - ^{232}Th is widely-available natural resource.
  - Released thermal power is 100 times that of beam energy.
  - Turning off the accelerator stops the fission reaction.



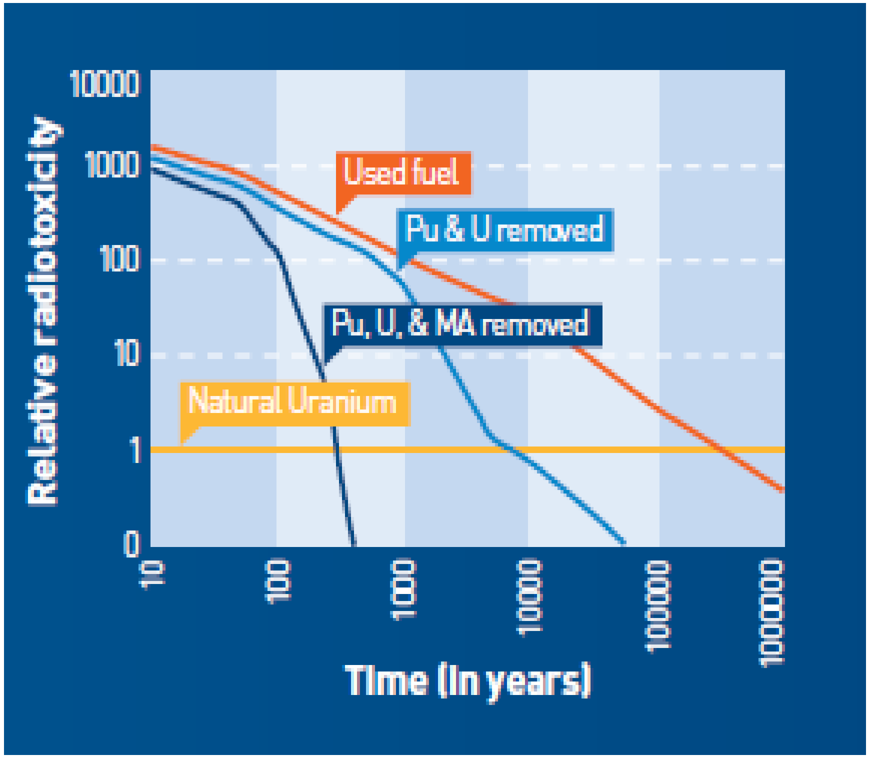
Use of Th instead of U produces less actinides.

The cycle produces much less long-lived radioactive waste (e.g. Pu).

Enough Th is available to sustain such systems for 10 centuries.

Accelerators for Energy

- ADSR & Radioactive Waste Transmutation
  - ADSR neutrons interact with surrounding fuel material containing separated long-lived isotopes.
    - Transmute these isotopes into shorter-lived products.



Accelerators for Energy

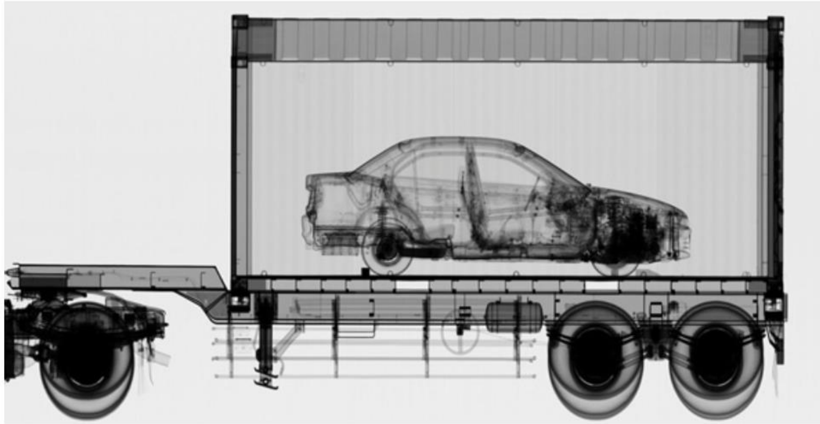
- International Thermonuclear Experimental Reactor (ITER)
  - Ion beams to be part of plasma heating techniques for fusion
    - Provide high current drive efficiency required magnetic confinement fusion facilities.
    - Required tens of A of ion current at 1 MeV kinetic energy.

Accelerators for the Environment

- CLOUD experiment at the CERN PS
  - Experiment using cloud chamber to study possible link between cosmic-rays and cloud formation.
    - Studies suggest that cosmic- rays may have an influence on the amount of cloud cover through the formation of new aerosols (tiny particles suspended in the air that seed cloud droplets).
  - Understanding the underlying microphysics in controlled laboratory conditions is a key to unraveling the connection between cosmic-rays, clouds and climate.
  - First time high-energy physics accelerator used to study atmospheric and climate science.

Accelerators for Security

X-ray Scanning of Cargo



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

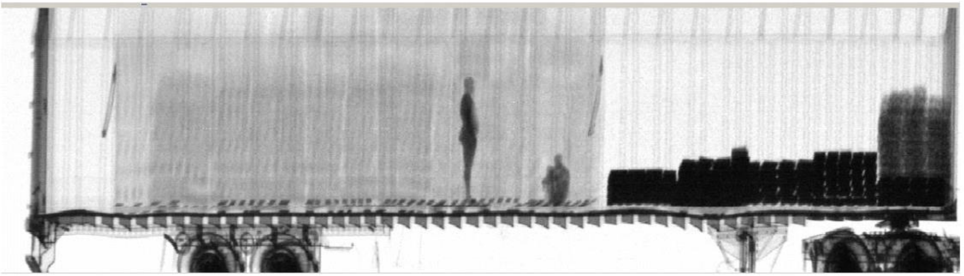
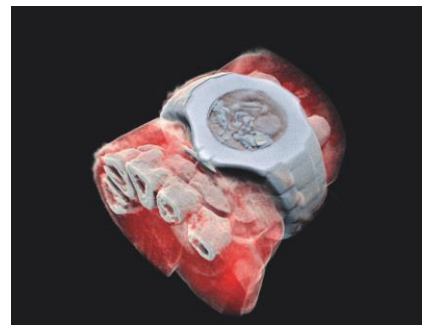


Image: dutch.euro

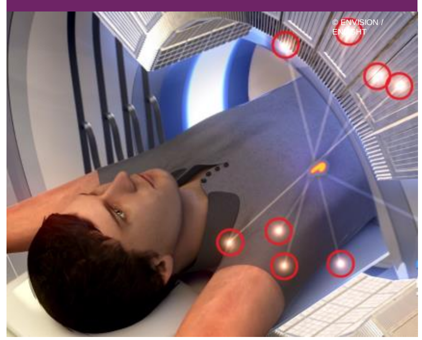
CERN’s technological innovations have important applications in medicine and healthcare

Technologies applied at CERN are also used in PET, for medical imaging and diagnostics.



CERN produces innovative radioisotopes for nuclear medicine research.

Accelerator technologies are applied in cancer radiotherapy with protons, ions and electrons.



Pixel detector technologies are used for high resolution 3D colour X-ray imaging.

Accelerators for Medicine

- X-ray Radiation Therapy
  - Electron linacs for conventional X-ray radiation therapy (MV photons).
  - X-rays have been used for decades to destroy tumours.

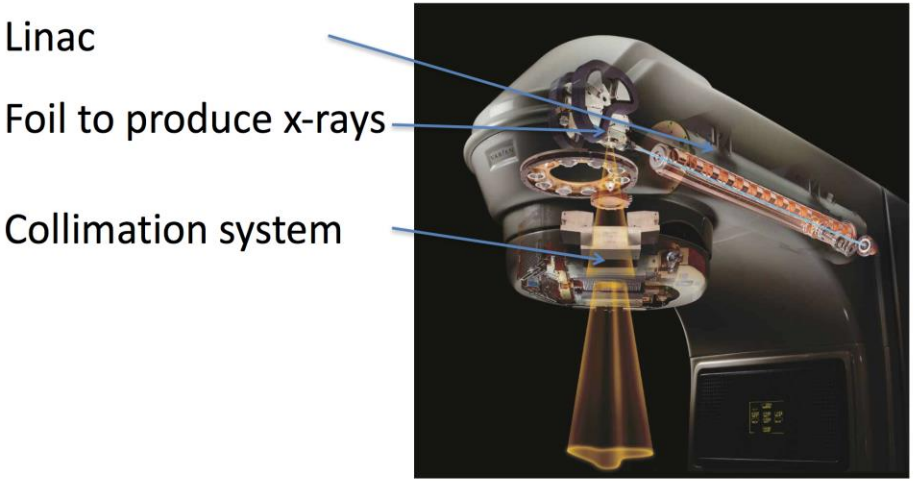
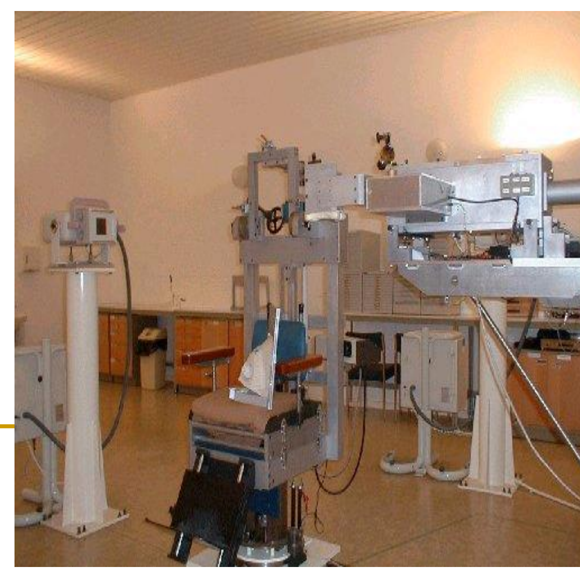


Image: copyright Varian medical systems

Accelerators for Medicine

- Hadrontherapy
  - For deep-seated tumours and/or minimizing dose in surrounding healthy tissue use hadrons (protons, light ions).
  - Accelerator-based hadrontherapy facilities.
  - Based on medium-energy cyclotrons and synchrotrons for hadron therapy with protons (250 MeV) or light ion beams (400 MeV/u 12C-ions

Loma Linda Proton Treatment Centre
Constructed at FNAL

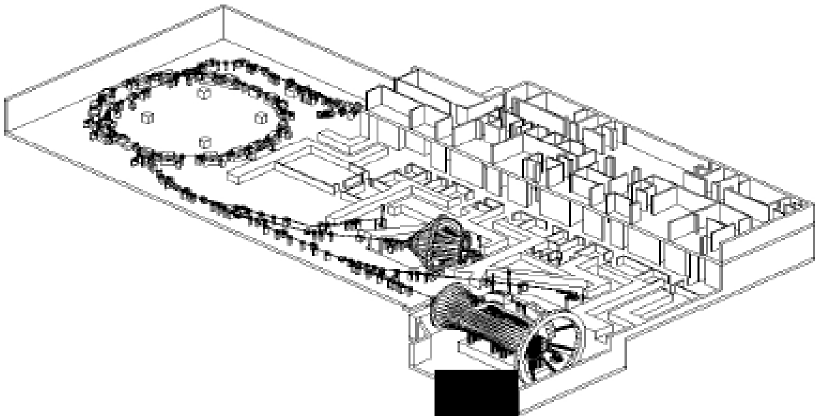


Established 1989
60 MeV protons

First hospital-based proton therapy

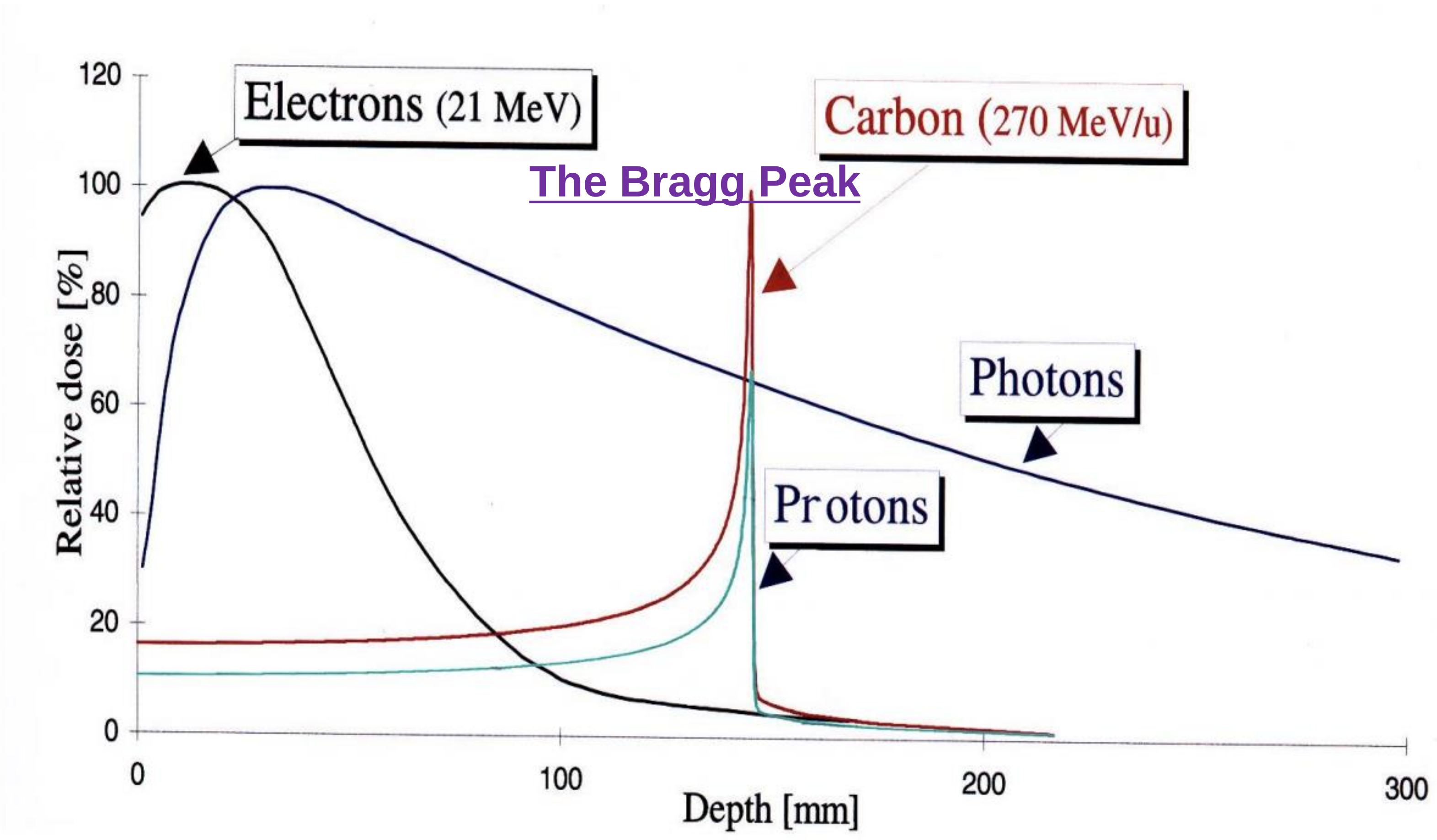
PIMMS @ CERN

Proton-Ion Medical Machine Study (PIMMS) Study



PIMMS (Proton-Ion Medical Machine Study) based at CERN
Members: CERN, TERA, Med-AUSTRON, collaboration with GSI.
Technical Design Report in 2000, CD-ROM of data and drawings.

Accelerators for Medicine



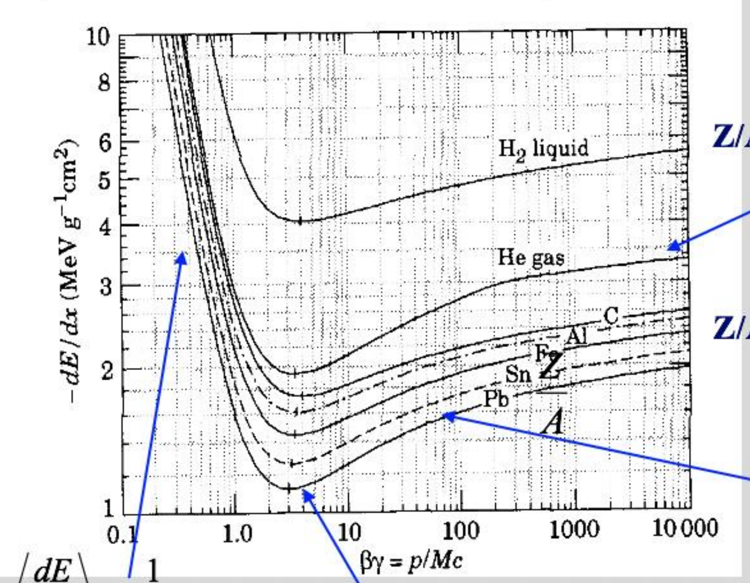
Accelerators for Medicine

Charged particle energy loss in matter
The relativistic Bethe-Bloch formula

Energy loss by Ionisation only → Bethe - Bloch formula

$$\left\langle \frac{dE}{dx} \right\rangle = -4\pi N_A r_e^2 m_e c^2 z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \gamma^2 \beta^2}{I^2} T^{\max} - \beta^2 - \frac{\delta}{2} \right]$$

- dE/dx in [MeV g^{-1} cm^2]
- valid for "heavy" particles ($m \geq m_\mu$).
- dE/dx depends only on β, independent of m !
- First approximation: medium simply characterized by Z/A ~ electron density



Z/A = 1

"Fermi plateau"

Z/A~0.5

$$\frac{Z}{A}$$

$$\left\langle \frac{dE}{dx} \right\rangle \propto \ln \beta^2 \gamma^2$$

"relativistic rise"

$$\left\langle \frac{dE}{dx} \right\rangle \propto \frac{1}{\beta^2}$$

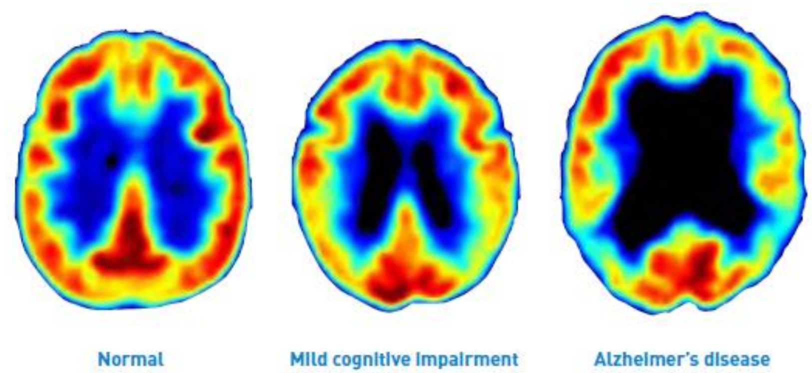
"kinematical term"

$\beta\gamma \approx$ 3-4
minimum ionizing particles, MIPs

Accelerators for Medicine

- Medical Imaging
  - Radioisotopes have become vital components in medicine.
    - Produced at reactors or accelerators (cyclotrons or linacs).
  - Positron Emission Tomography (PET)
    - Requires positron emitter ^{18}F
    - From 7-11 MeV proton accelerator
  - ^{99}Mo / ^{99m}Tc
    - 100 kW of 200 MeV protons impinging on depleted U target produce neutrons.
    - Neutrons targeted on low-enriched U thus producing ^{99}Mo.

Bone scans indicating increased ^{99m}Tc intake due to cancer growth



PET Scan

Radiopharmaceuticals

p, d, 3He, 4He beams

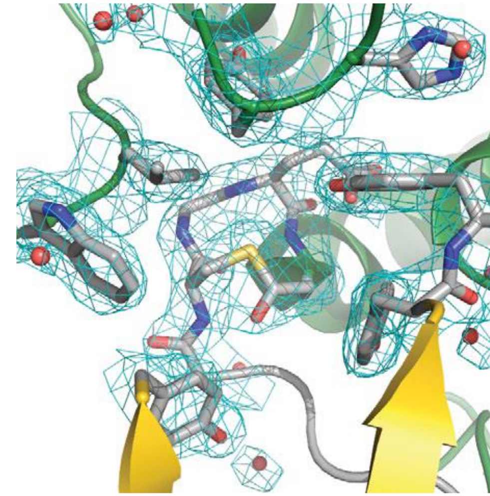
Isotopes used for PET, SPECT and Brachytherapy etc…

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**	

Neutrons & X-rays

Protein structure revealed with help of light sources

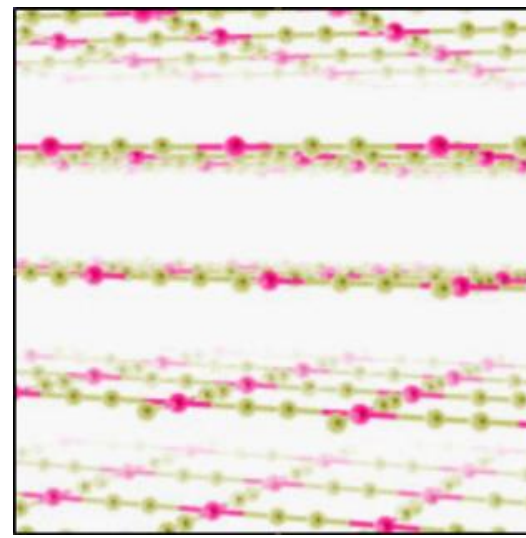


ISIS and Diamond neutron and X-ray sources
Harwell, UK

Neutron and X-ray imaging essential for studies of proteins and advanced materials.

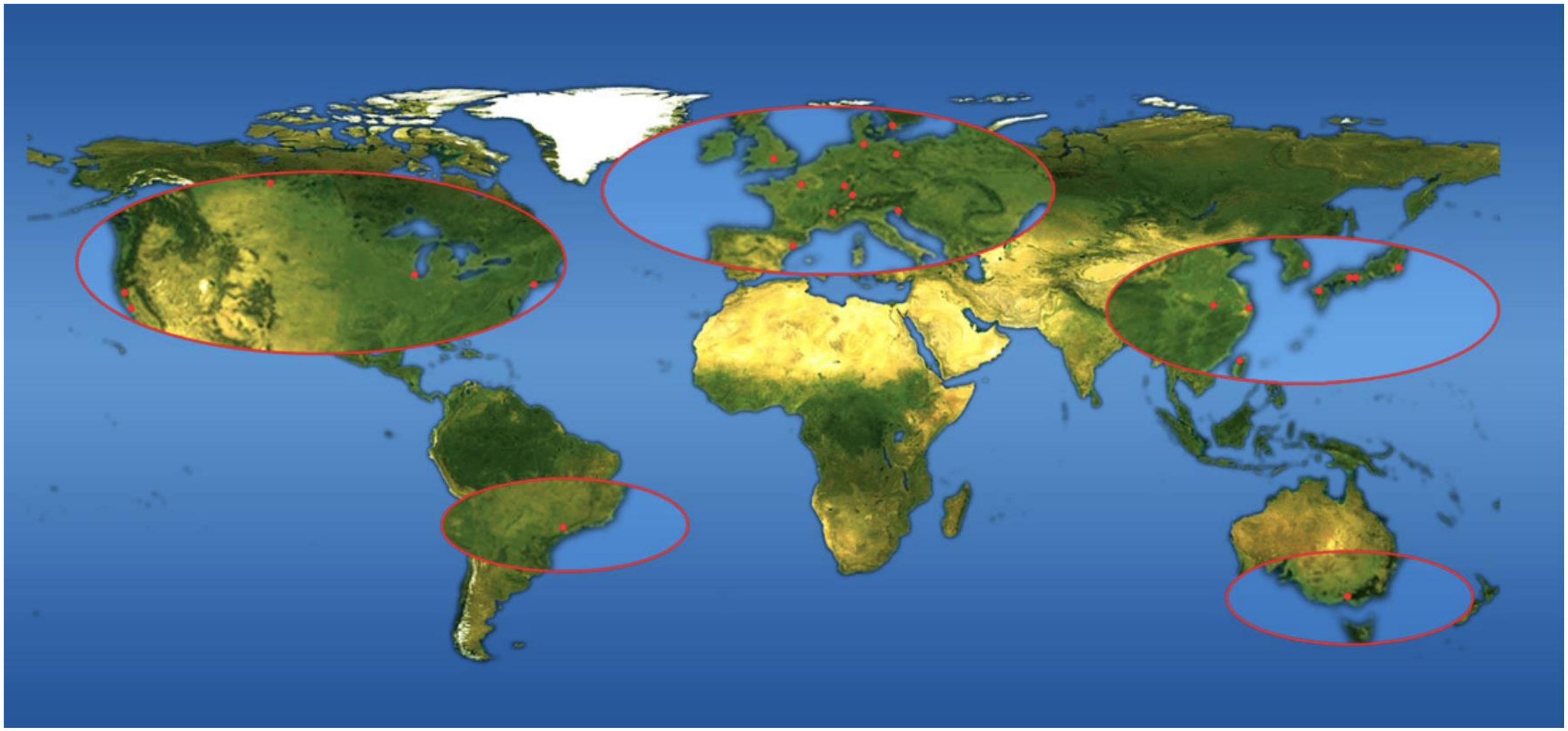
diamond

Science & Technology Facilities Council



2-d material (graphene)

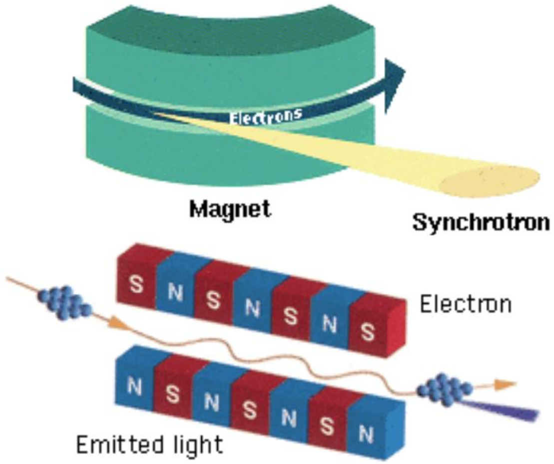
Synchrotron Light Sources

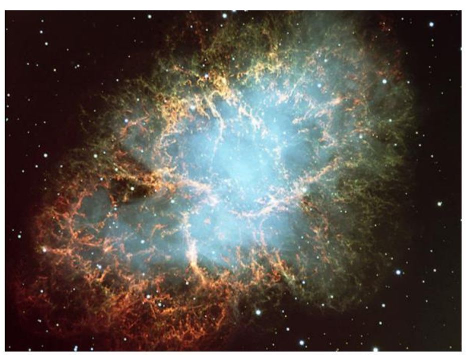


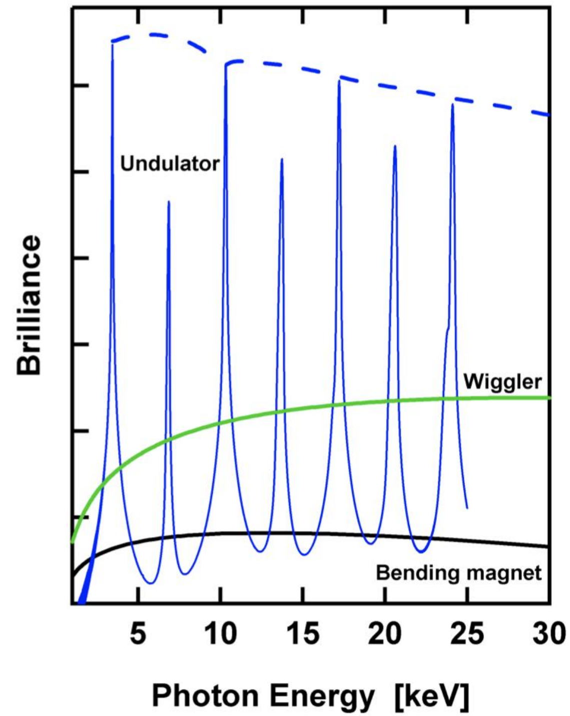
Courtesy ESRF

Synchrotron Light Sources

Synchrotron radiation is emitted by charged particles when accelerated radially

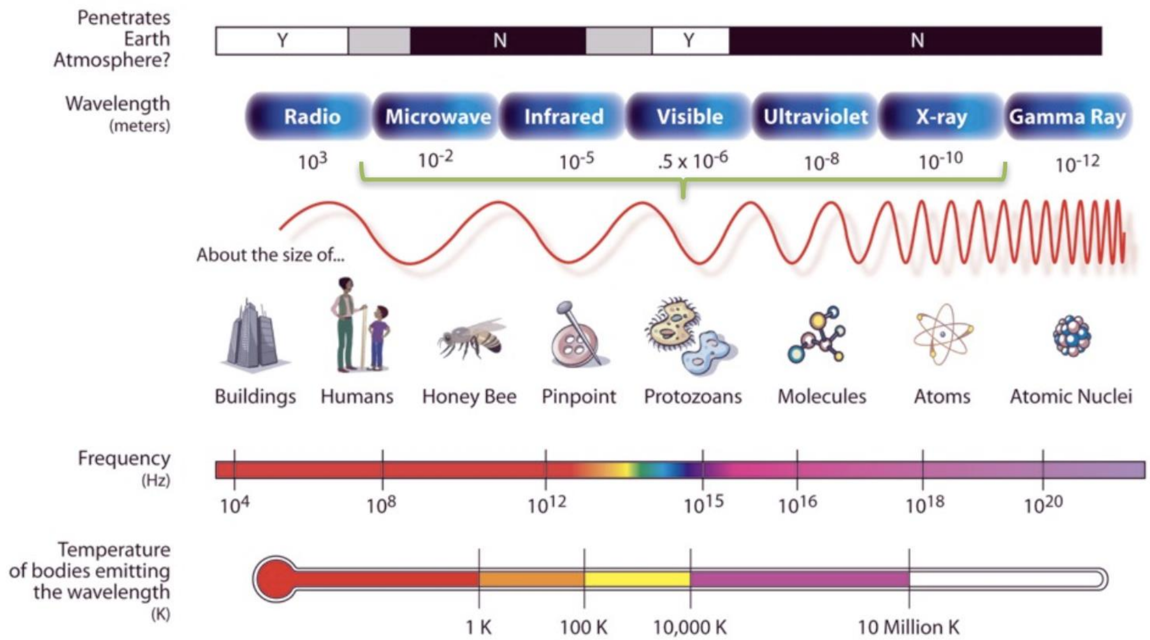






Produced in synchrotron radiation sources using bending magnets, undulators and wigglers

The Electromagnetic Spectrum



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

High flux = quick experiments!

Pulsed structure = resolution of processes down to picoseconds

Rate of Energy Loss (1)

- This **EM radiation** generates an **energy loss** of the particle concerned, which can be calculated using:

$$P = \left(\frac{2}{3}\frac{rc}{(m_0 c^2)^3}\right) E^2 F^2$$

constant

Electron radius
Velocity of light
Total energy
'Accelerating' force
Lepton rest mass

- Force can be written as: **F = evB = ecB**
- Thus: $P = \left(\frac{2}{3}\frac{e^2 r c^3}{(m_0 c^2)^3}\right) E^2 B^2$ but $(B\rho) = \frac{p}{e} = \frac{E\beta}{ec}$

$$\frac{v}{c} = 1$$

- Which gives: $P = \left(\frac{2}{3}\frac{rc}{(m_0 c^2)^3}\right) \frac{E^4}{\rho^2}$

Rate of Energy Loss (2)

- Have: $$P=\left(\frac{2}{3}\frac{rc}{\left(m_0c^2\right)^3}\right)\frac{E^4}{\rho^2}$$,which gives the energy loss

- Interested in the energy loss per revolution for which need to integrate the above over one turn.

- Thus: $$\int P dt=\int P\frac{ds}{c}$$

- However: $$\int\frac{ds}{c}=2\pi\int\frac{d\rho}{c}$$

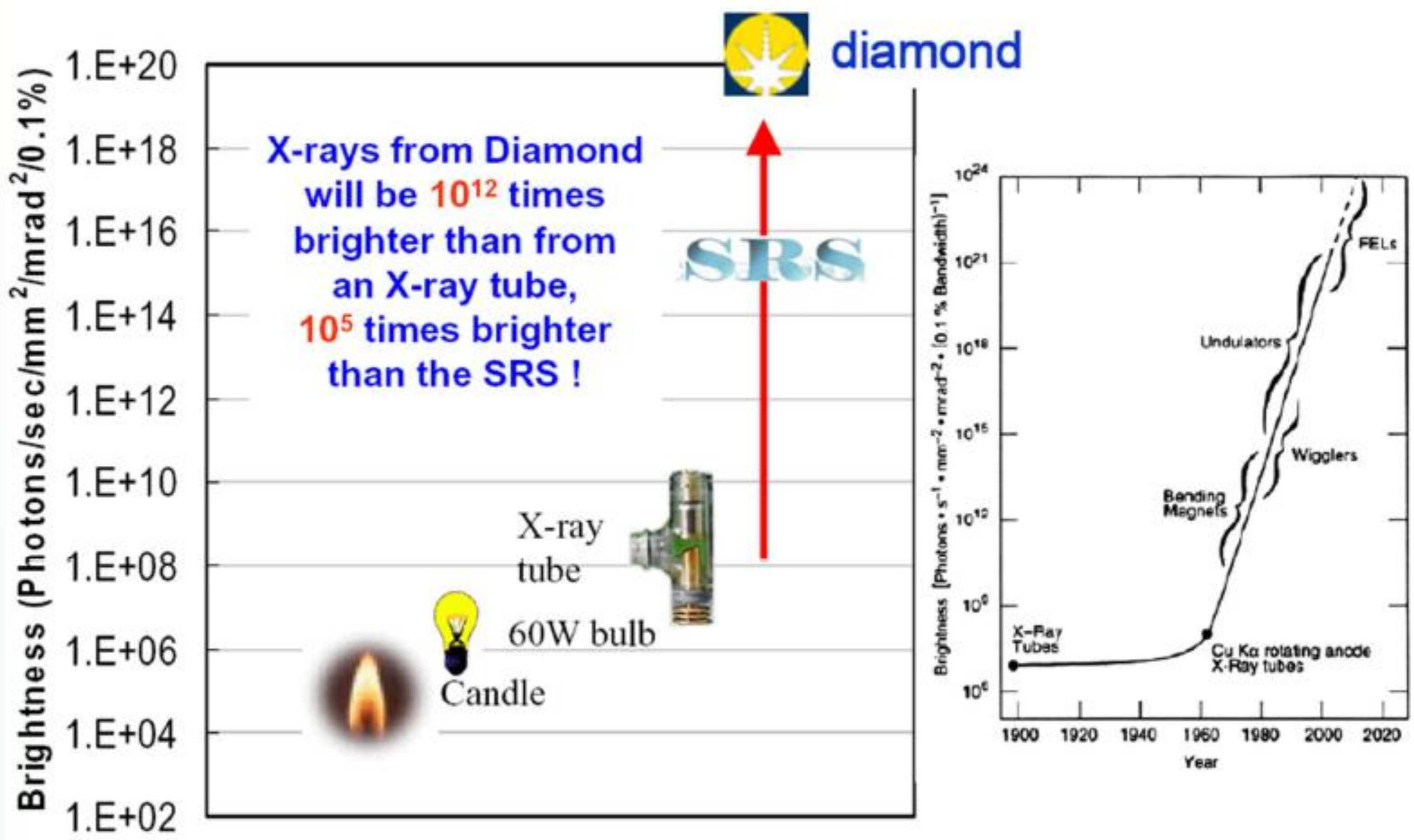
- Finally, this gives: $$u=\underbrace{\frac{4\pi}{3}\frac{r}{\left(m_0c^2\right)^3}}_{C}E^4\int\frac{1}{\rho^2}d\rho \quad =-\frac{CE^4}{\rho}$$

Bending radius inside the magnets

Lepton energy

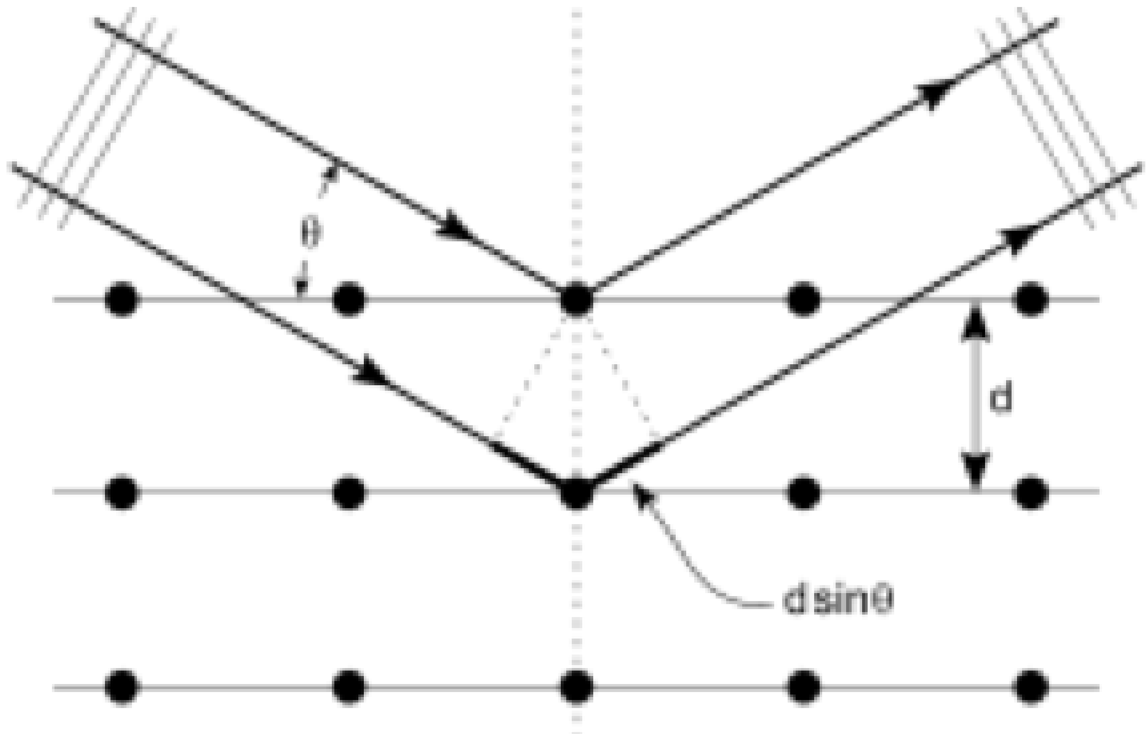
Gets very large if E is large !!!

Accelerators for Synchrotron Light



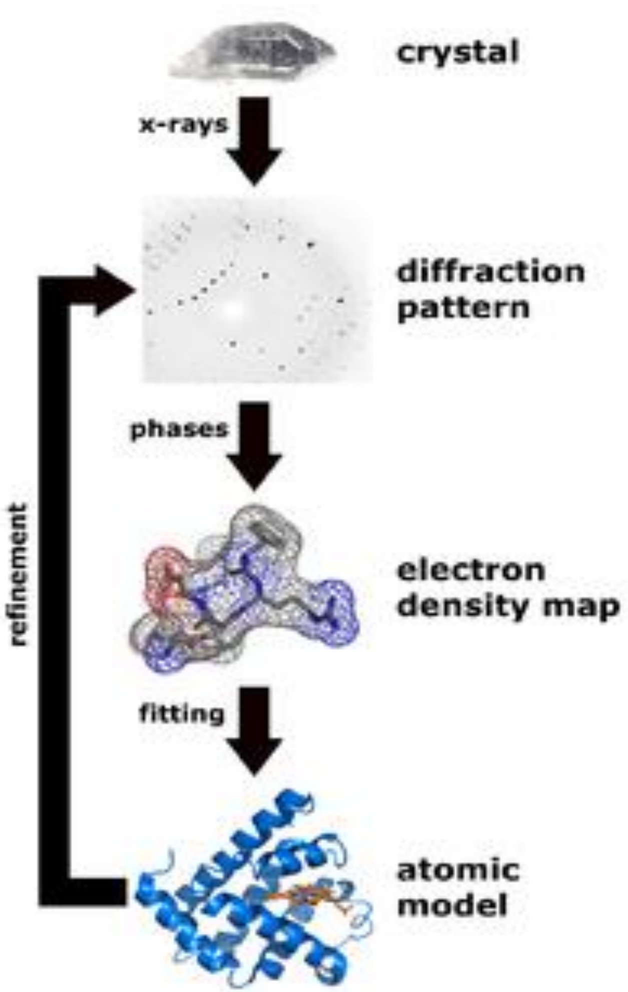
X-ray Diffraction

Max von Laue
1914 Nobel Prize:
'For his discovery of the diffraction of X-rays by crystals'



Constructive interference:
$2\,d\,\sin\theta = n\,\lambda$

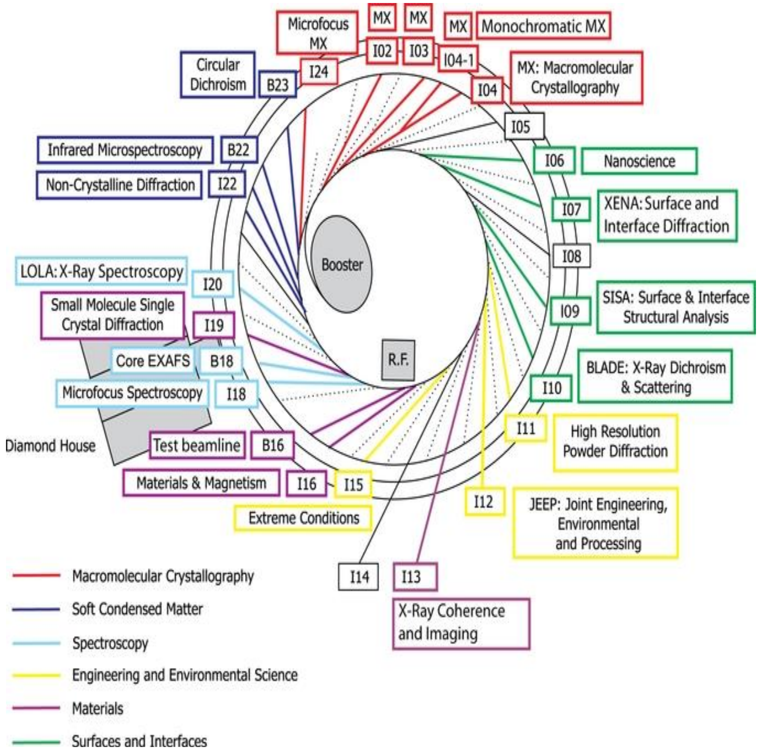
X-ray Diffraction Today



Diamond Light Source

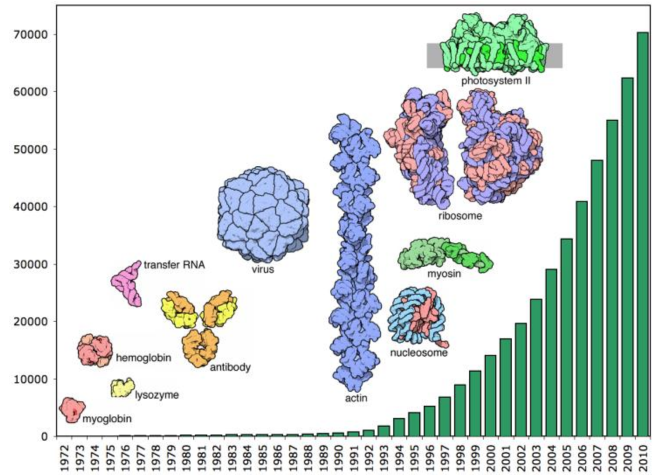
Diamond Light Source, Harwell Science and Innovation Campus, UK

Diamond Light Source Beamlines

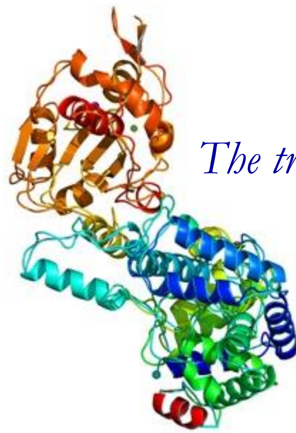


Accelerators for Synchrotron Light

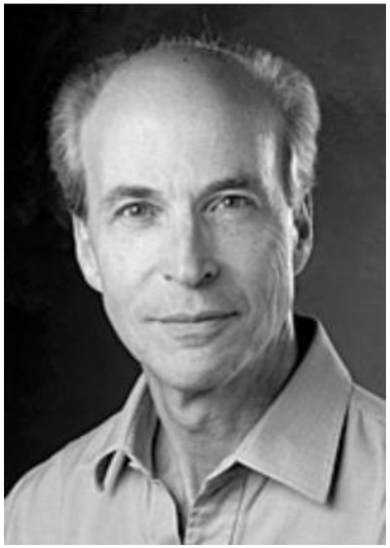
- Protein Structures
  - Proteins are biological molecules involved in almost every cellular process.
  - The protein is produced, crystallised and illuminated by X-rays. The interactions between the X-rays and the crystal form a pattern that can be analysed to deduce the protein structure.
  - Over 45,000 structures have been solved by the worldwide synchrotron community.



Protein Data Bank

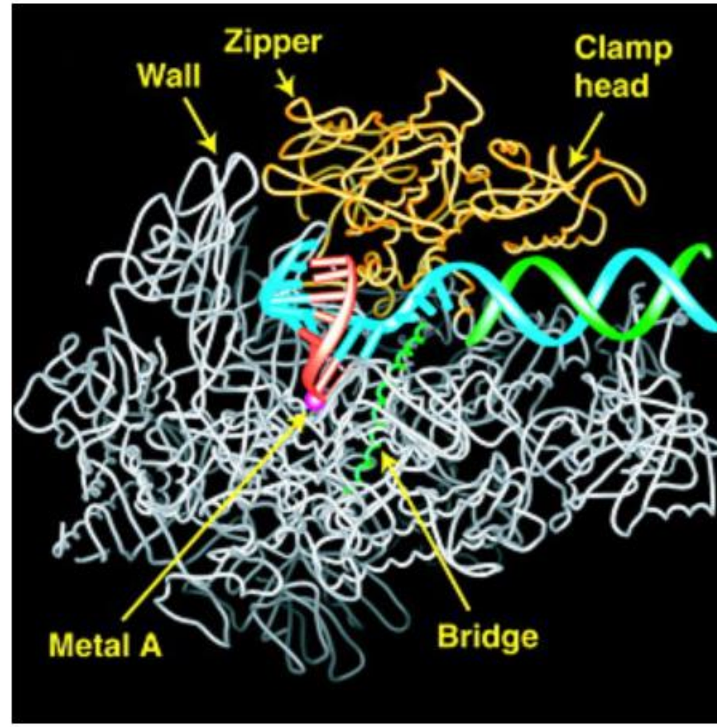


The trimer of the Lassa nucleoprotein, part of the Lassa virus



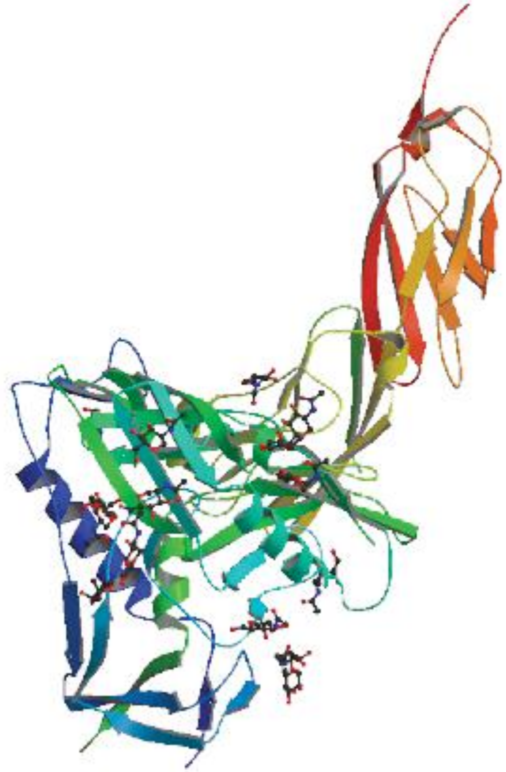
Roger Kornberg's Nobel Prize-winning determination of the structure of RNA polymerase has been described as a "technical tour de force." The key to the visualization of this fundamental biological molecule in action was synchrotron radiation, supplied by the powerful X-ray crystallography instruments at the Stanford Synchrotron Radiation Laboratory.

Science

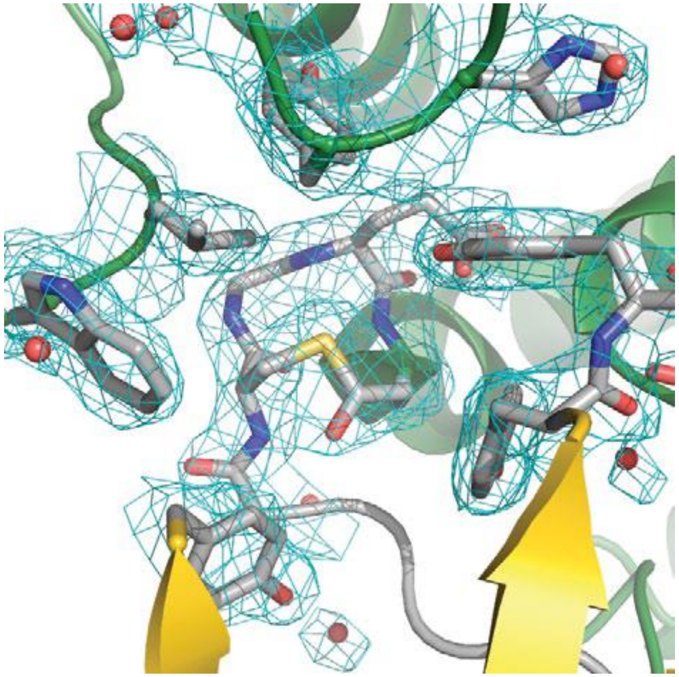


The transcription process visualized by Roger Kornberg and his colleagues in his X-ray crystallography studies published online April 19, 2001, in *Science*. The protein chain shown in grey is RNA polymerase, with the portion that clamps on the DNA shaded in yellow. The DNA helix being unwound and transcribed by RNA polymerase is shown in green and blue, and the growing RNA stand is shown in red.

Protein Structure Revealed by Light Sources



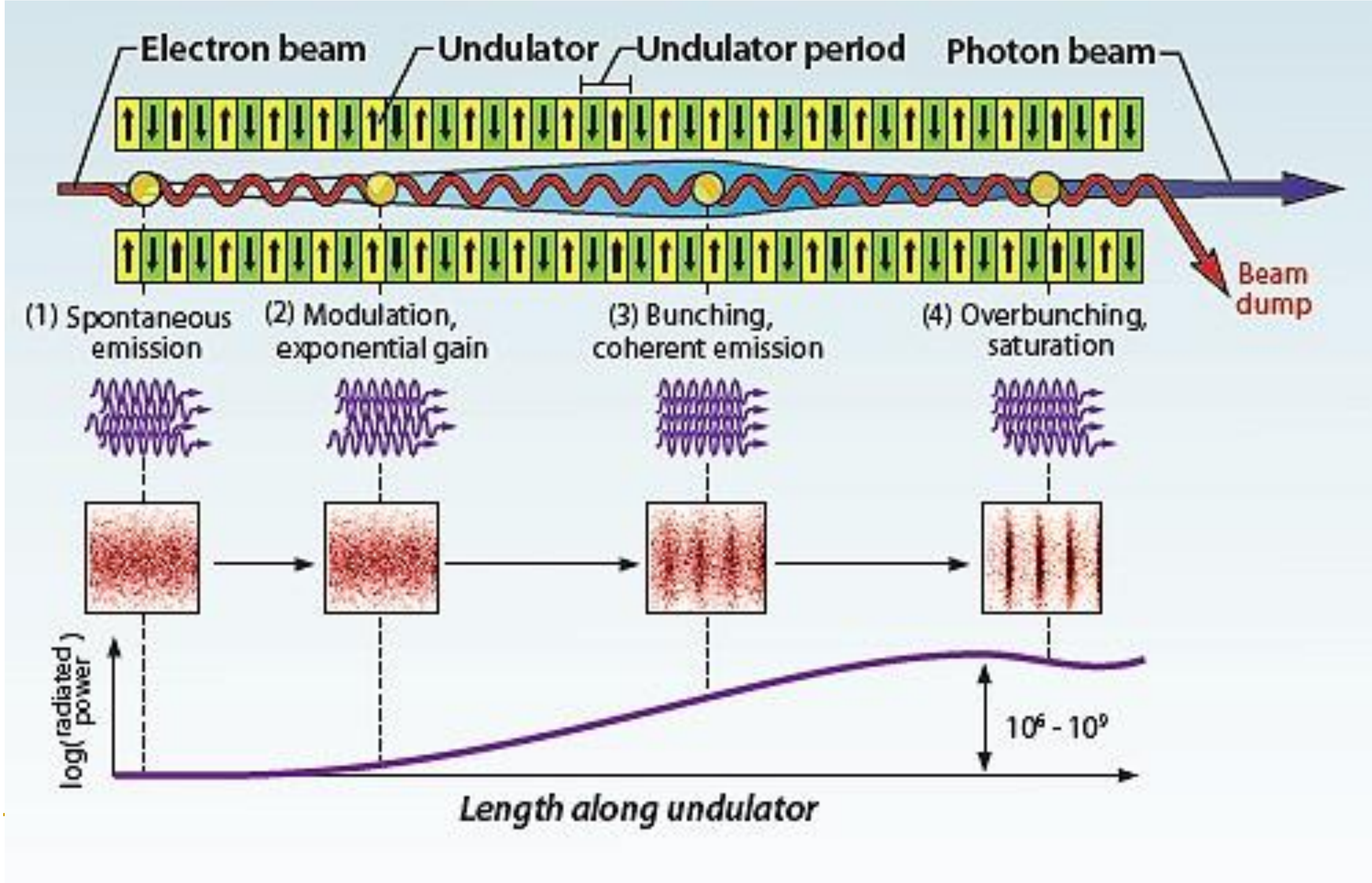
HIV glycoprotein



mosquito
immune system

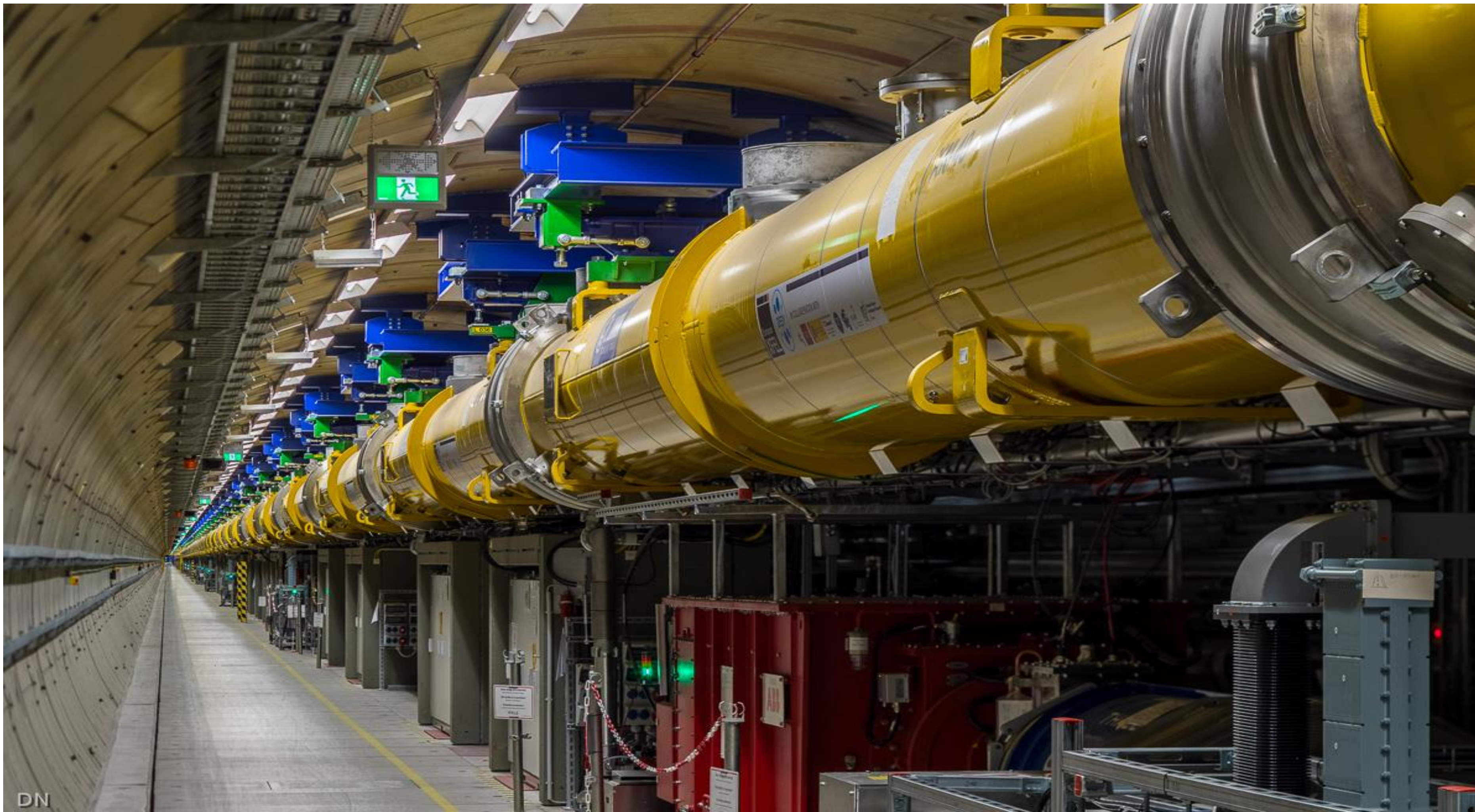
yeast enzyme

4^{th} Generation Light Source – Free Electron Laser



European XFEL

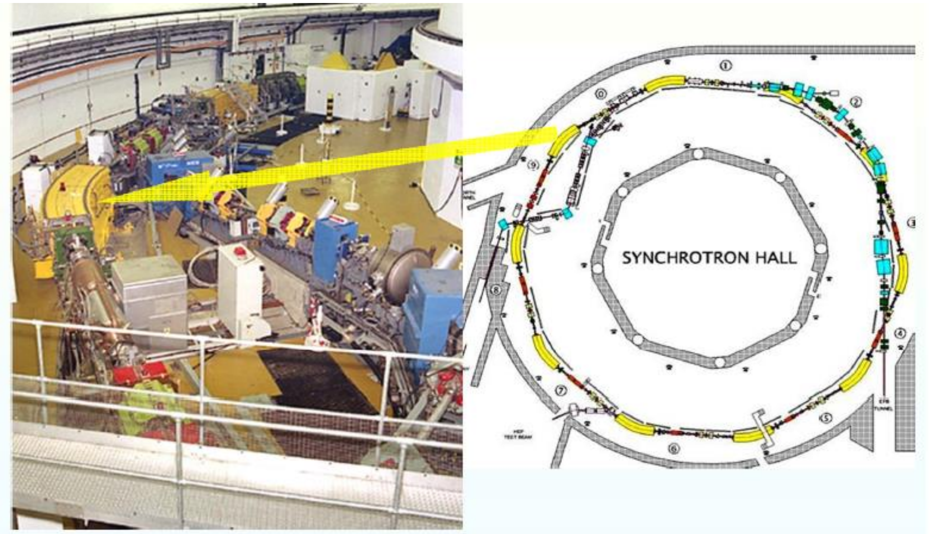
- **European XFEL at DESY is a large-scale proto-type for the ILC**
  - **100 cryomodules; 23.6 MV/m, accelerator length 2.1 km; 17.5 GeV**
  - **Sucessfully started operation in 2017**

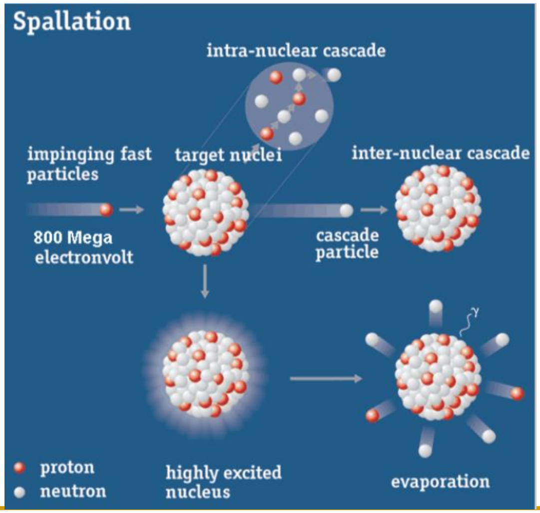


Accelerators for Neutron Science

ISIS Spallation Facility (800 MeV) at RAL

- Penetrate deep inside materials since they are deflected only from the nuclei of atoms.
- Statistical observation of deflected neutrons at various positions after the sample can be used to find the structure of a material.
- Loss or gain of energy by neutrons can reveal the dynamic behaviour of parts of a sample, for example dynamic processes of molecules in motion.

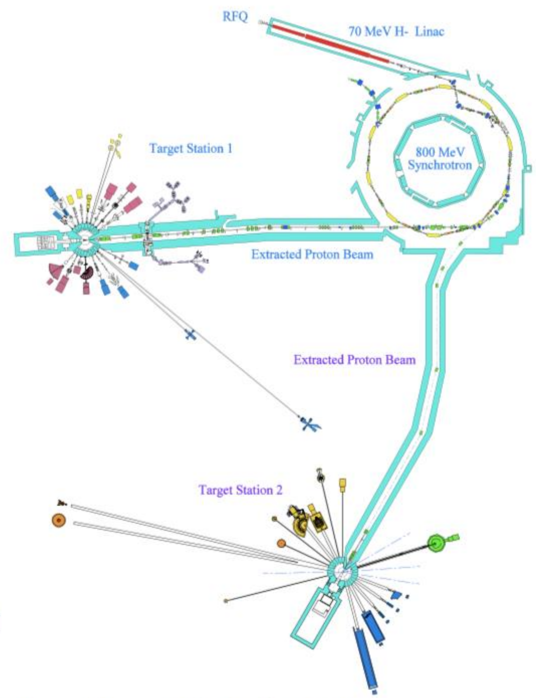




ISIS Accelerators and Targets

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).

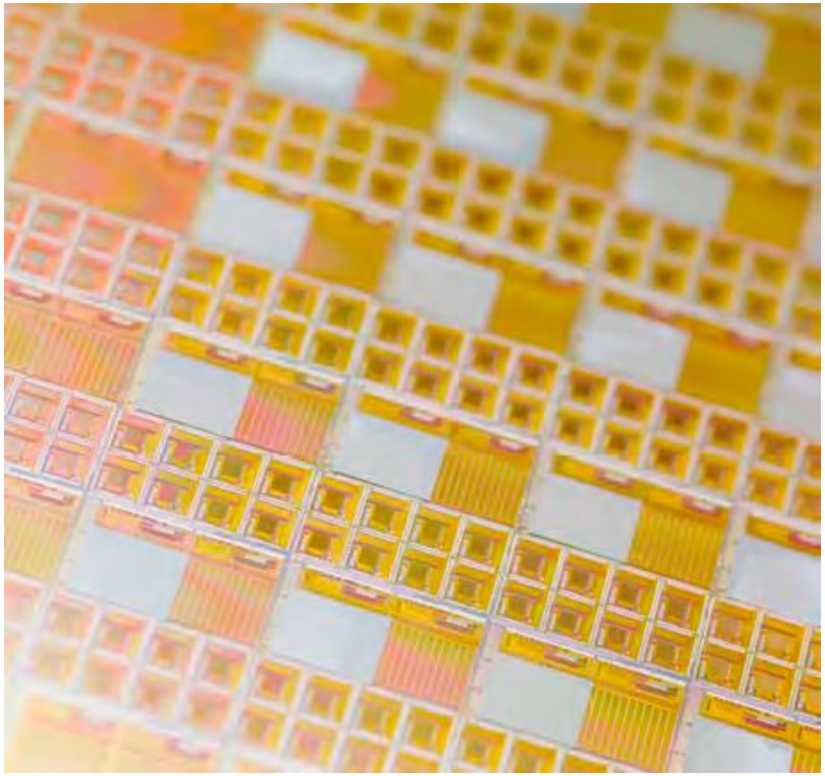
$$P = 800[MV] \times 230[\mu A] = 184[kW]$$

Accelerators for Ion Beam Implantation

- Ion implantation in semiconductor manufacture
- Typical semiconductor fabrication:
  140 operations, 70 involving ion implantation at specific sites in crystal
- Ions accelerated to modest energies

  Depth of implant controlled by ion beam energy: typically 2 → 600 keV

Ion Beam Implantation Products



Radiocarbon ^{14}C Formation & 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

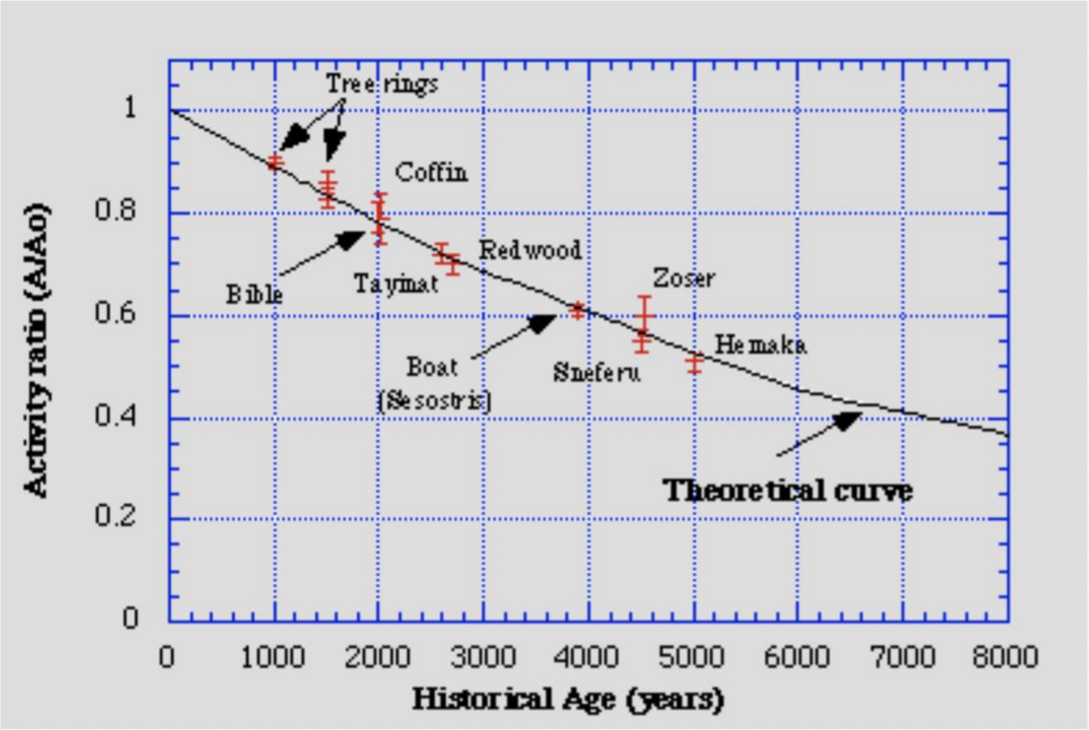
$$^{14}_{6}C \rightarrow ^{14}_{7}N + \beta^- + \bar{\nu} + Q$$

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.

Radiocarbon ^{14}C 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.

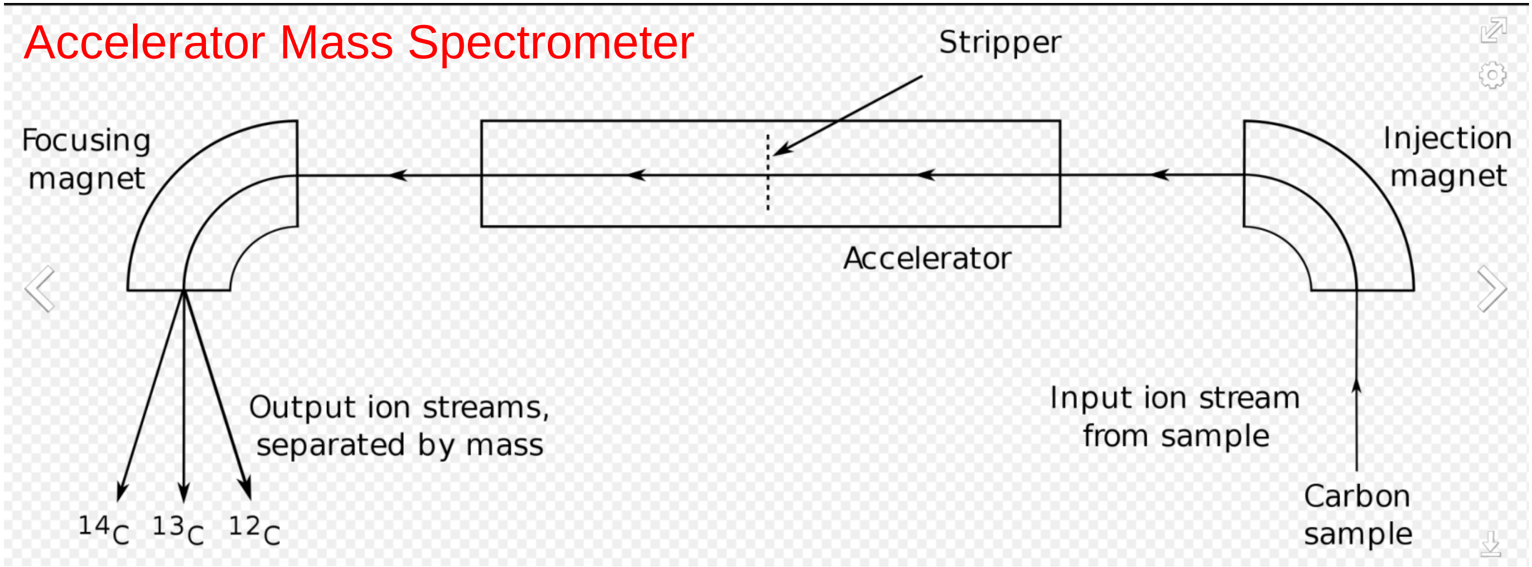


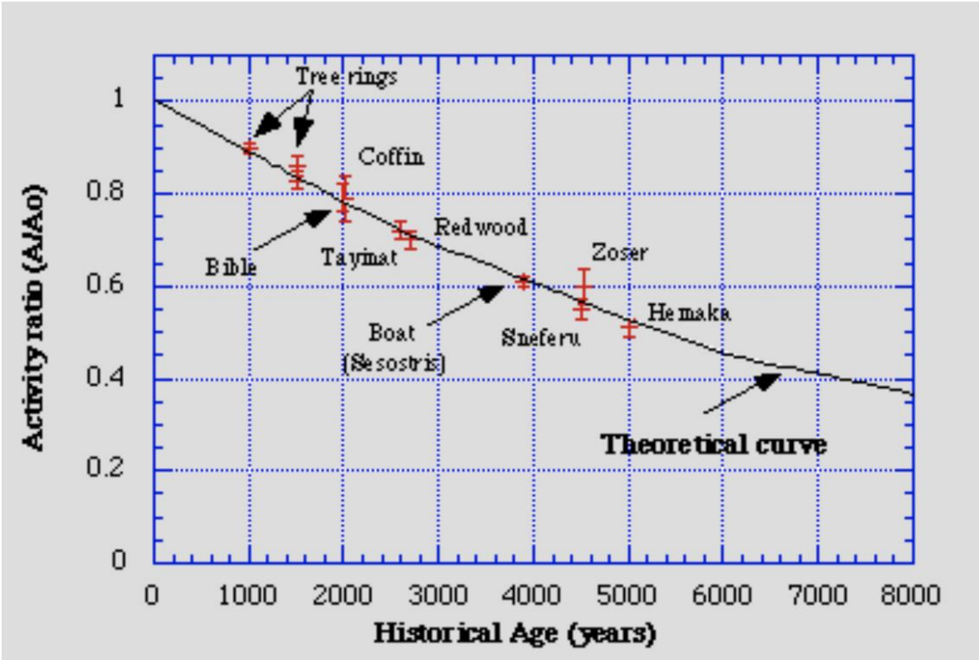
$$A = A_0 e^{-\lambda t}$$

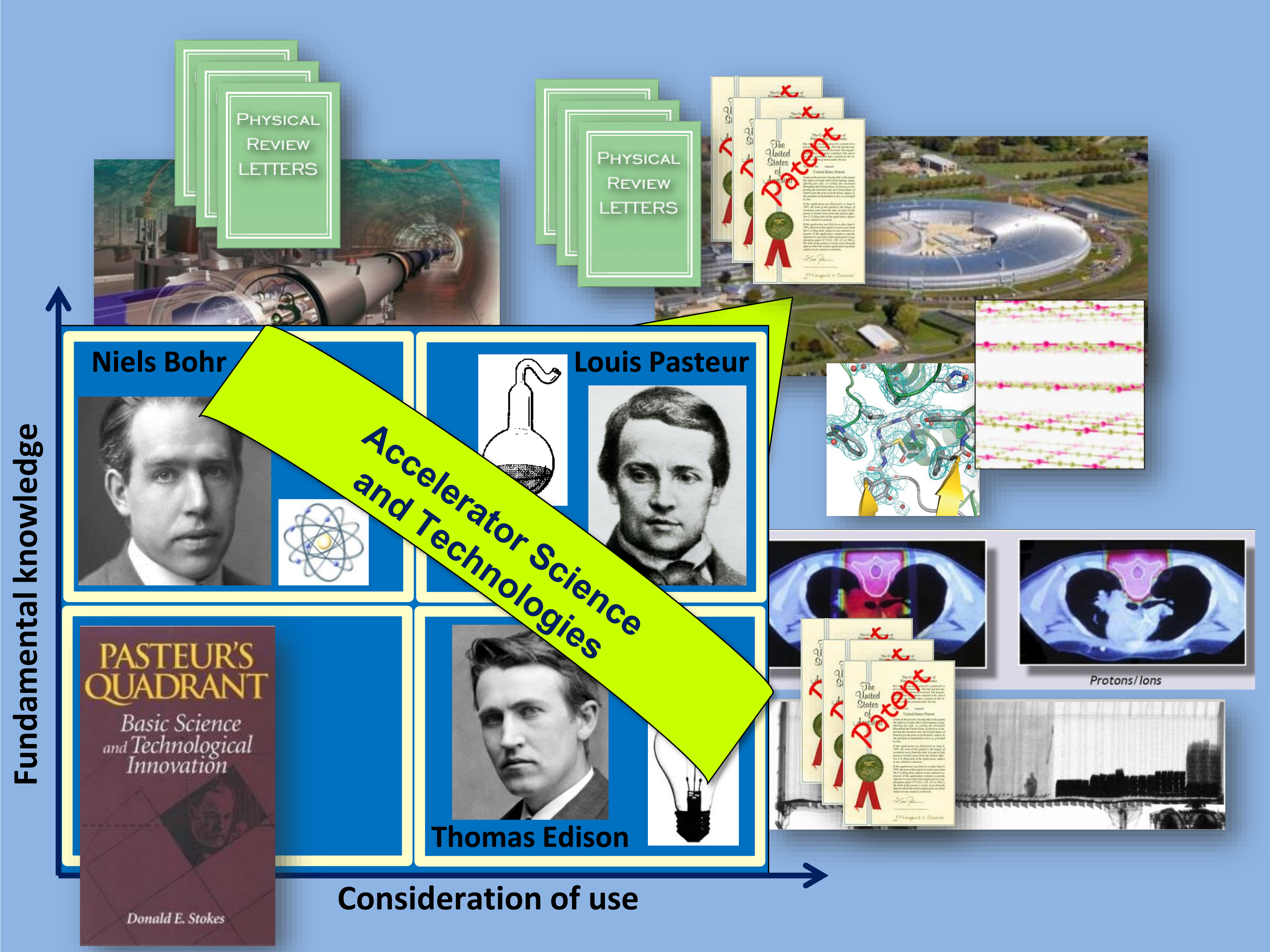
where present-day, pre-bomb, ^{14}C activity = 13.56dpm/g C

Accelerators for History & Culture Applications

Radiocarbon Dating






Physical Review Letters
Physical Review Letters
Patent
Patent
Niels Bohr
Louis Pasteur
Accelerator Science and Technologies
Thomas Edison
Pasteur's Quadrant
Basic Science and Technological Innovation
Donald E. Stokes
Protons/Ions
Fundamental knowledge
Consideration of use

Bibliography