
Lecture 2

Applications of Accelerators

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Graduate Accelerator Physics Course
John Adams Institute for Accelerator Science
14 October 2021

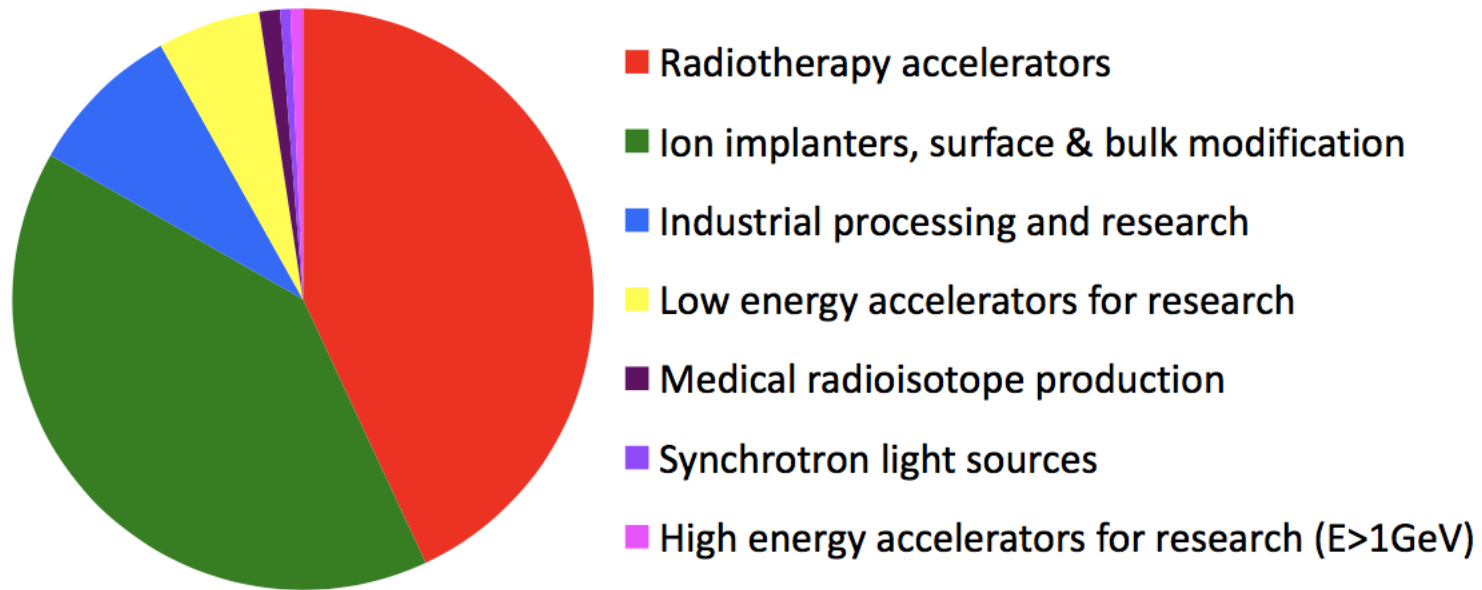


Introduction



Accelerators Worldwide

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

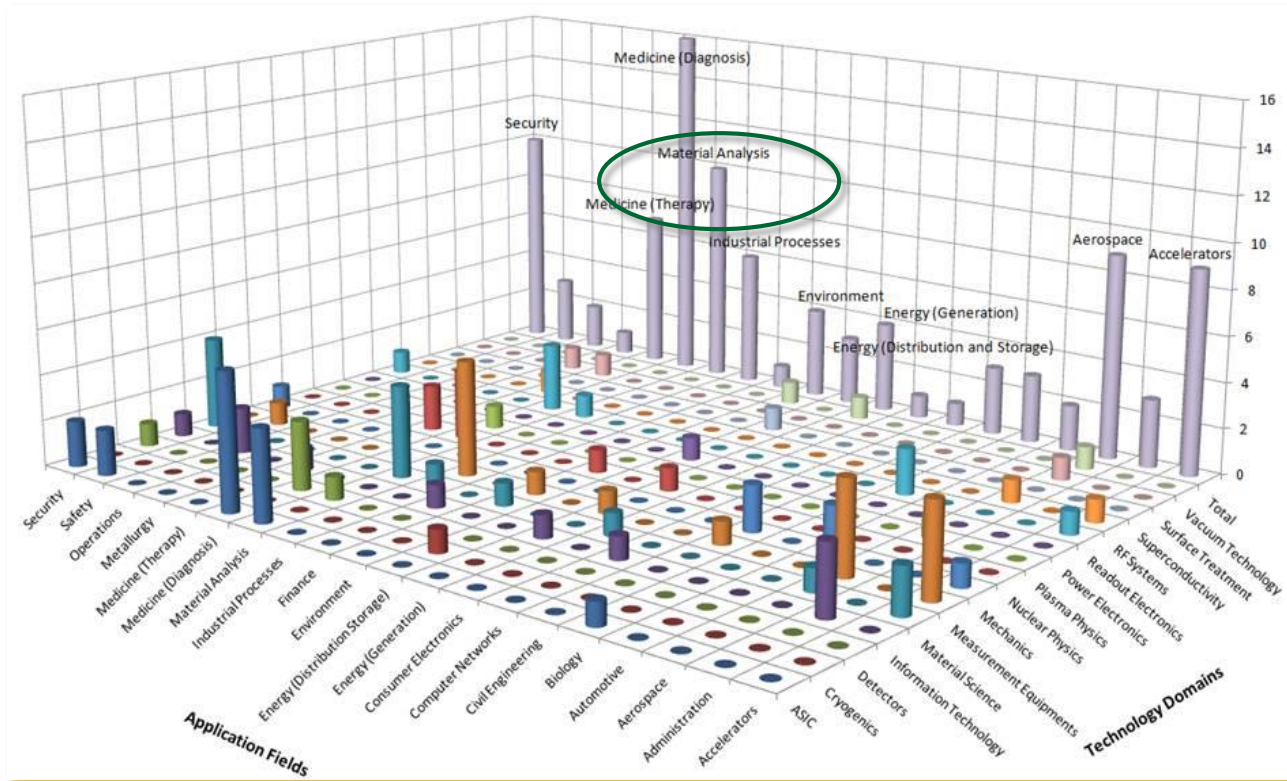


There are roughly 35,000 accelerators in the world
(Above 1 MeV...)

Accelerators are not only for particle physics

Accelerator Technologies and Innovation

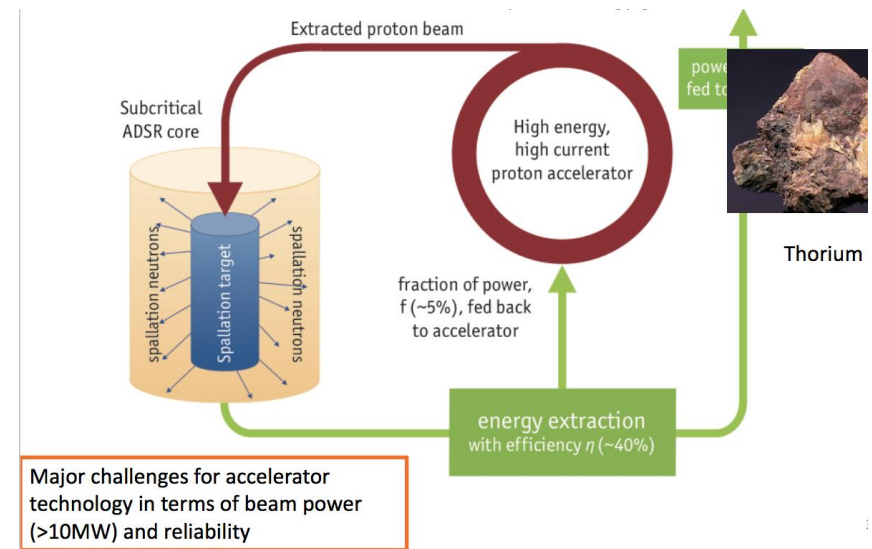
Cutting edge Research Infrastructures play a key role in a knowledge driven society



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.



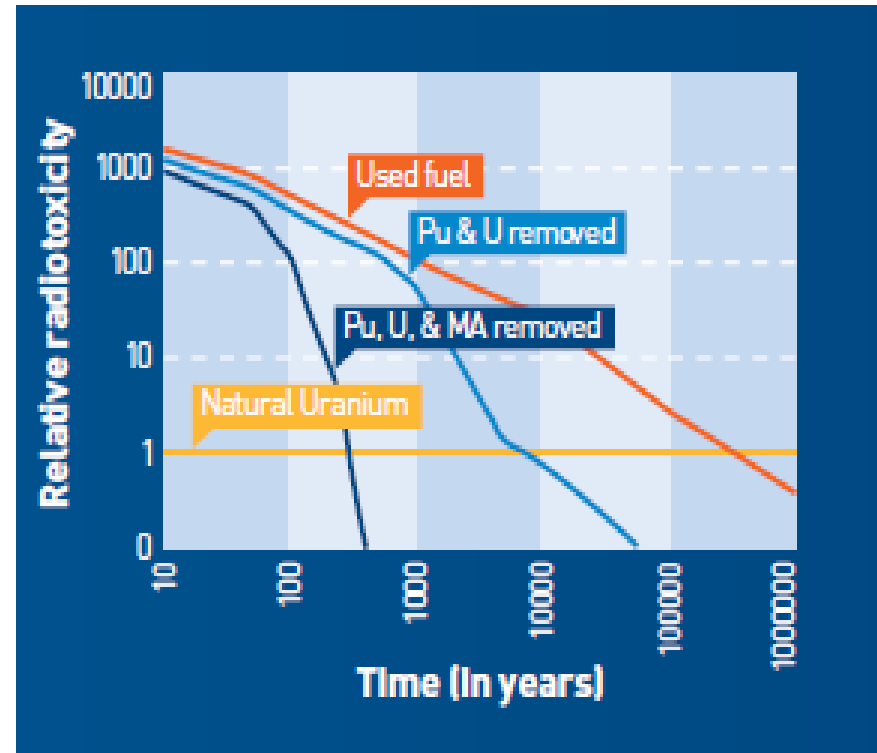
Use of Th instead of U produces less actinides.

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

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

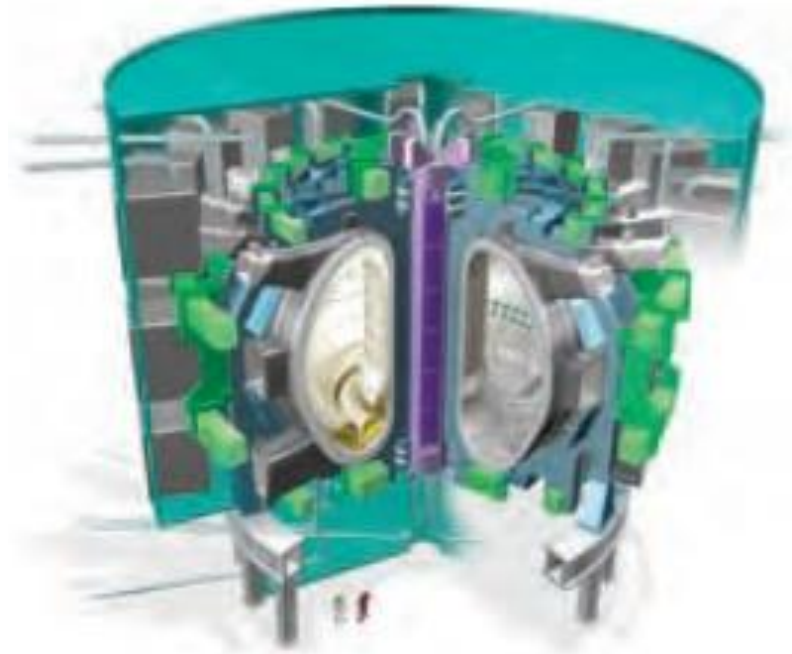
Accelerators for Energy

- 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.



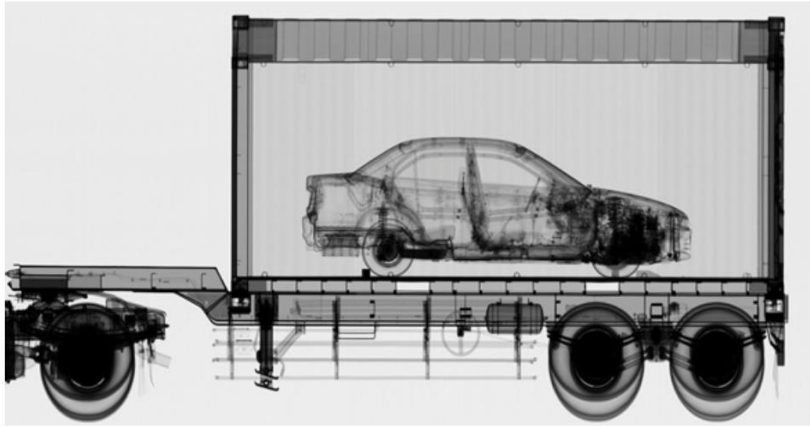
Accelerators for the Environment

- 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

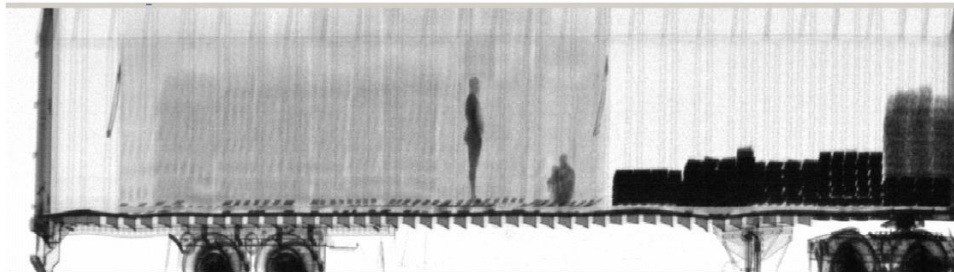
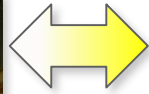


Image: dutch.euro

Accelerators for Medicine

Combining Physics, ICT, Biology and Medicine to fight cancer

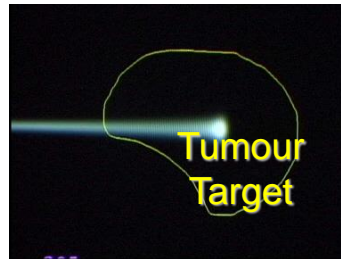


Hadron Therapy

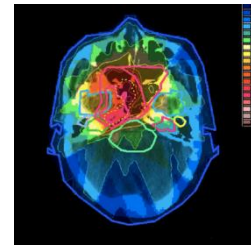
Accelerating particle beams

~35'000 accelerators worldwide

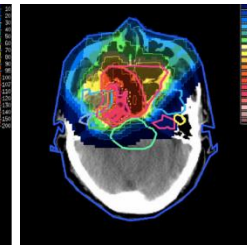
~17'000 used for medicine



Protons
light ions



X-ray

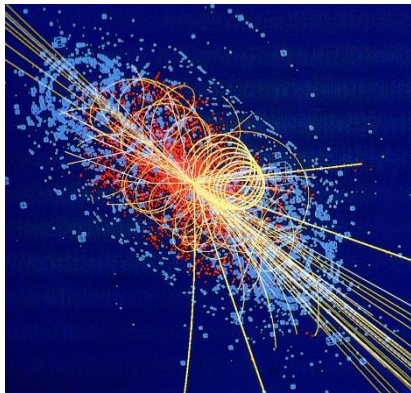


protons

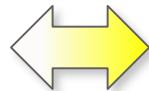
Leadership in Ion
Beam Therapy now in
Europe and Japan

>100'000 patients treated worldwide (45 facilities)

>50'000 patients treated in Europe (14 facilities)



Detecting particles

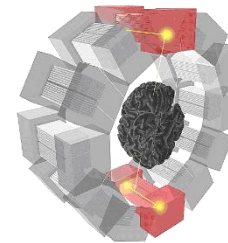


Imaging

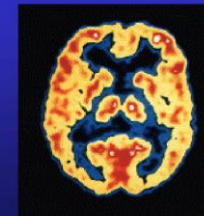
Clinical trial in Portugal, France and
Italy for new breast imaging system
(ClearPEM)



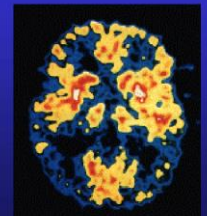
PET Scanner



Brain Metabolism in Alzheimer's Disease: PET Scan



Normal Brain



Alzheimer's Disease

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.

Linac

Foil to produce x-rays

Collimation system

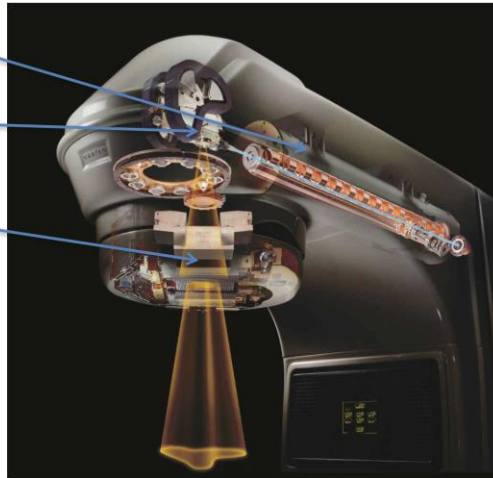


Image: copyright Varian medical systems



Accelerators for Medicine

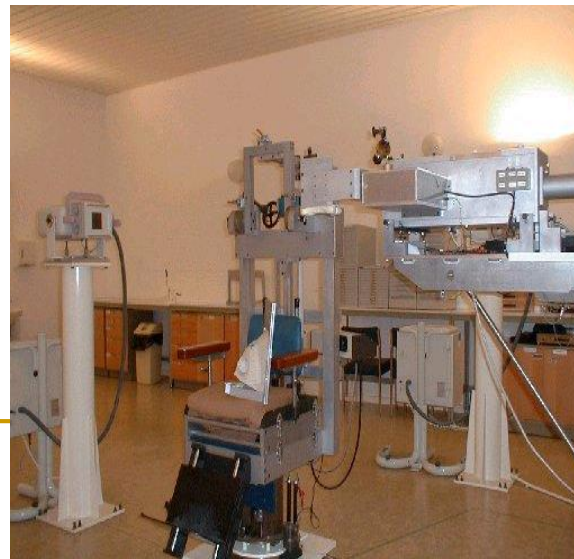
■ Hadrontherapy

- 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 ^{12}C -ions)



COURTESY LOMA LINDA UNIVERSITY MEDICAL CENTER

Loma Linda Proton Treatment Centre
Constructed at FNAL

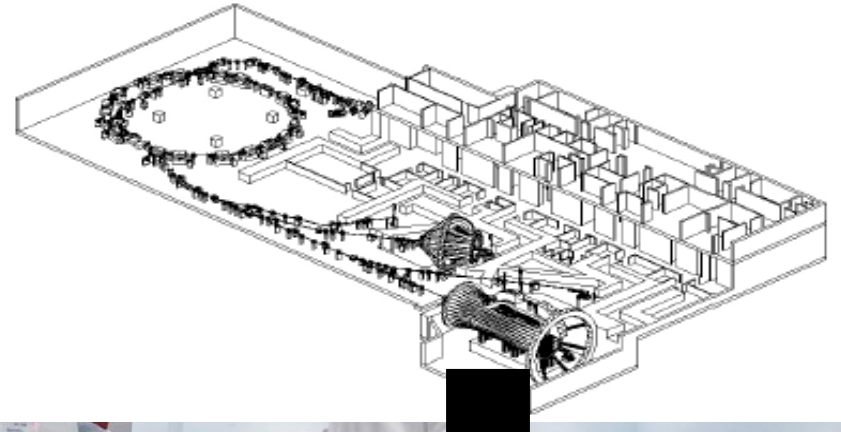


Established 1989
60 MeV protons

First hospital-based
proton therapy

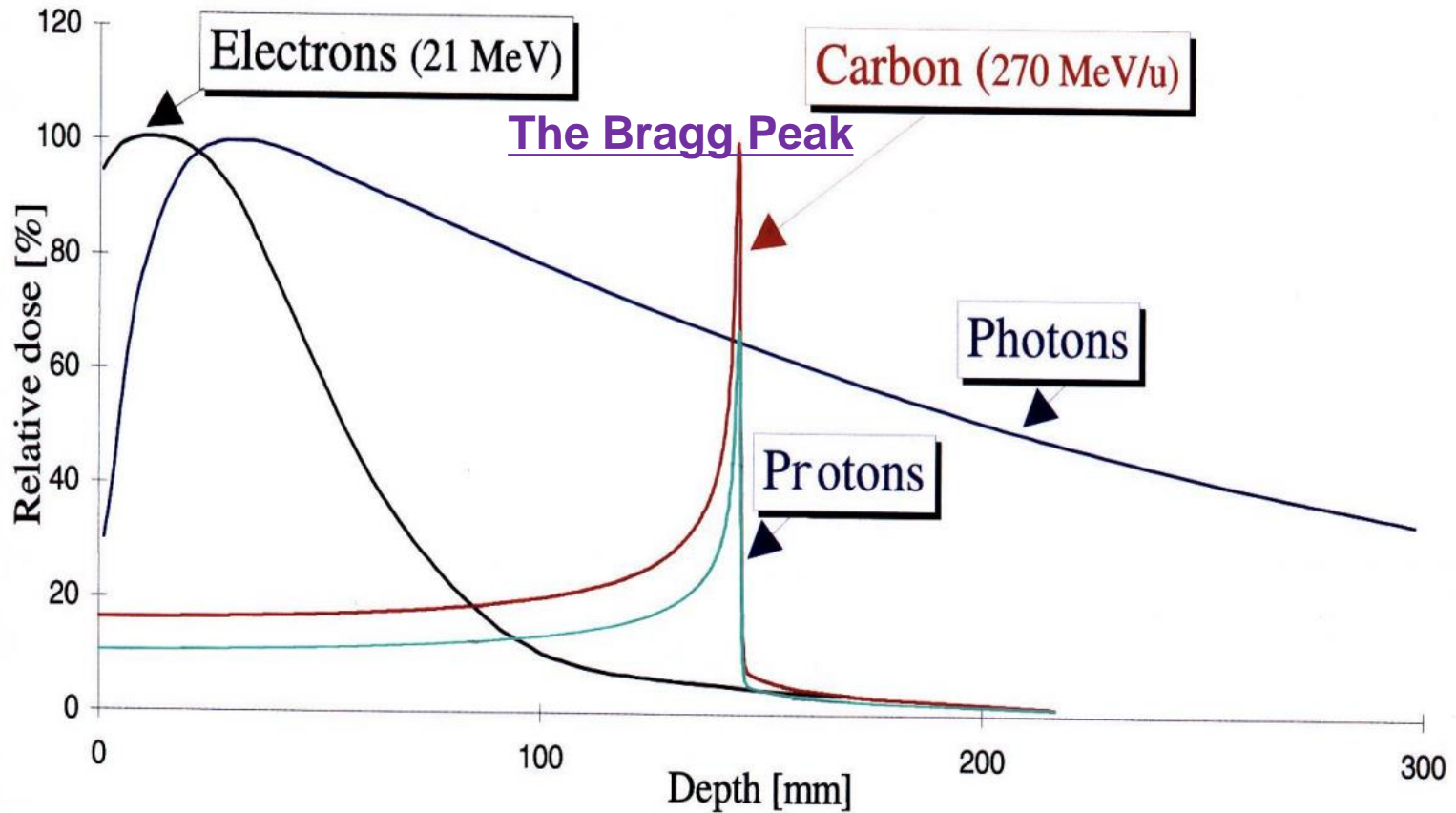
PIMMS @ CERN

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



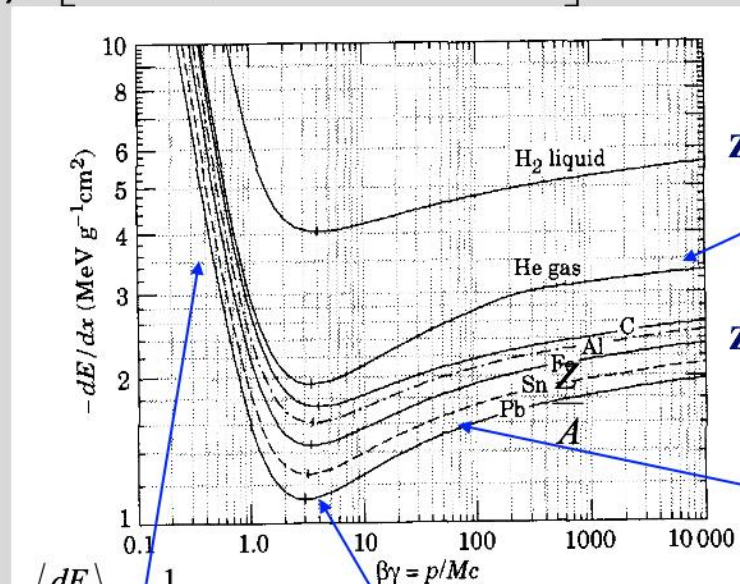
Accelerators for Medicine

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

Energy loss by Ionisation only → Bethe - Bloch formula

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

- ◆ dE/dx in [MeV g⁻¹ cm²]
- ◆ valid for “heavy” particles (m ≥ m_μ).
- ◆ 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

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

“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

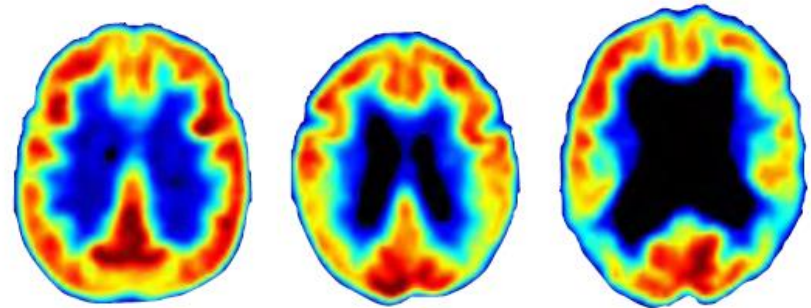
Accelerators for Medicine

■ 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 / $^{99\text{m}}\text{Tc}$
 - 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 $^{99\text{m}}\text{Tc}$ intake due to cancer growth



Normal

Mild cognitive impairment

Alzheimer's disease

PET Scan

Radiopharmaceuticals

p, d, ^3He , ^4He
beams

Isotopes used for PET,
SPECT and Brachytherapy
etc...



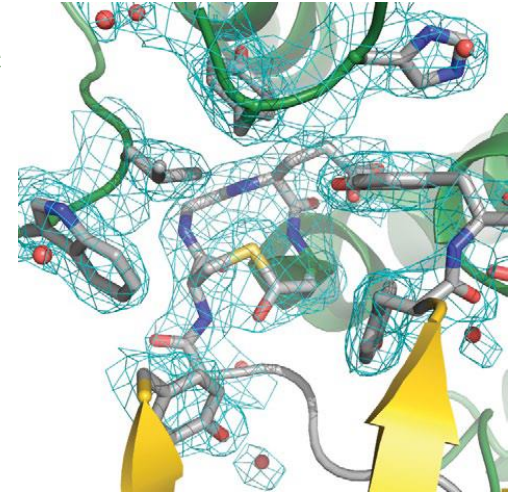
TABLE 2.1. THE RADIOISOTOPES THAT HAVE BEEN USED AS TRACERS IN THE PHYSICAL AND BIOLOGICAL SCIENCES

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

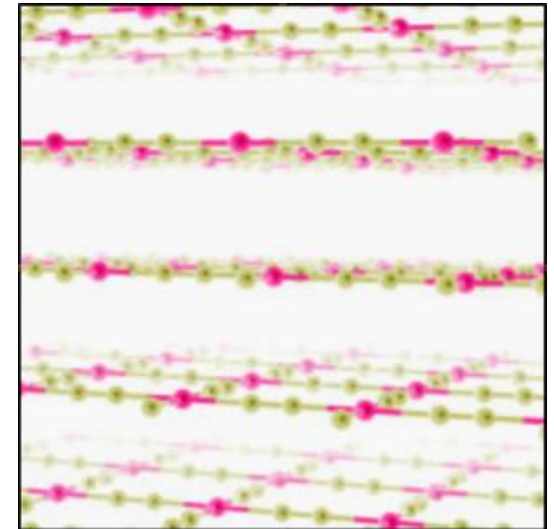


Protein structure
revealed with help of
light sources



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

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



2-d material (graphene)



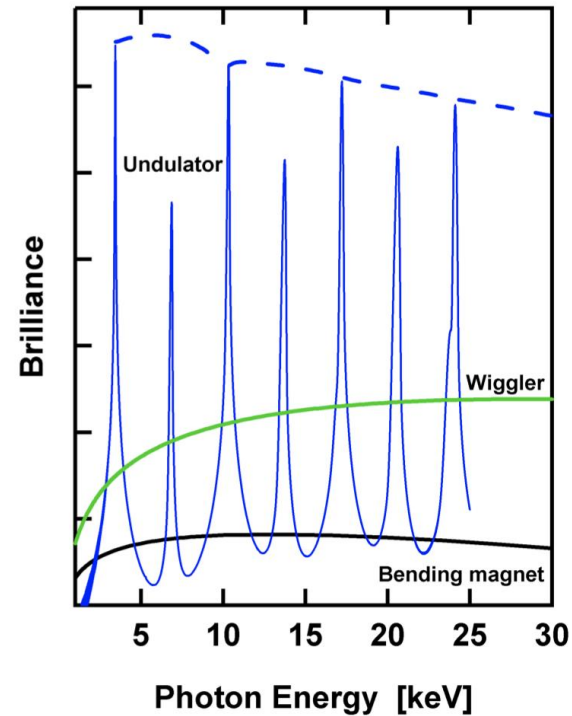
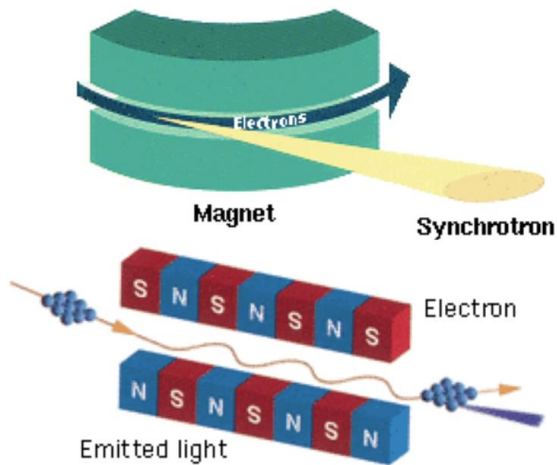
Synchrotron Light Sources



Courtesy ESRF

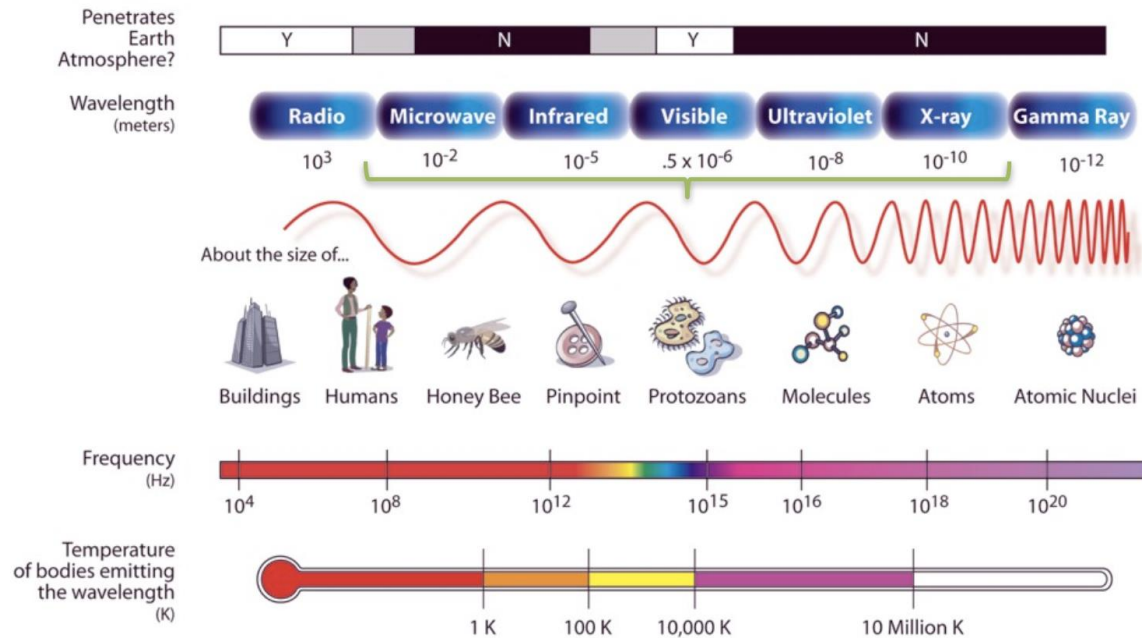
Synchrotron Light Sources

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:

The diagram shows the formula $P = \left(\frac{2}{3} \frac{rc}{(m_0 c^2)^3} \right) E^2 F^2$ with labels pointing to its parts:

- constant**: points to the fraction $\frac{2}{3}$.
- Electron radius**: points to r .
- Velocity of light**: points to c .
- Total energy**: points to E .
- 'Accelerating' force**: points to F .
- Lepton rest mass**: points to m_0 .

Force can be written as: $\mathbf{F} = e\mathbf{v}\mathbf{B} = e\mathbf{c}\mathbf{B}$

Thus:
$$P = \left(\frac{2}{3} \frac{e^2 rc^3}{(m_0 c^2)^3} \right) E^2 B^2 \quad \text{but} \quad (B\rho) = \frac{p}{e} = \frac{E\beta}{ec}$$

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

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: $P = \left(\frac{2}{3} \frac{rc}{(m_0 c^2)^3} \right) E^4 \rho^2$, which gives the energy loss

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

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

Bending radius inside the magnets

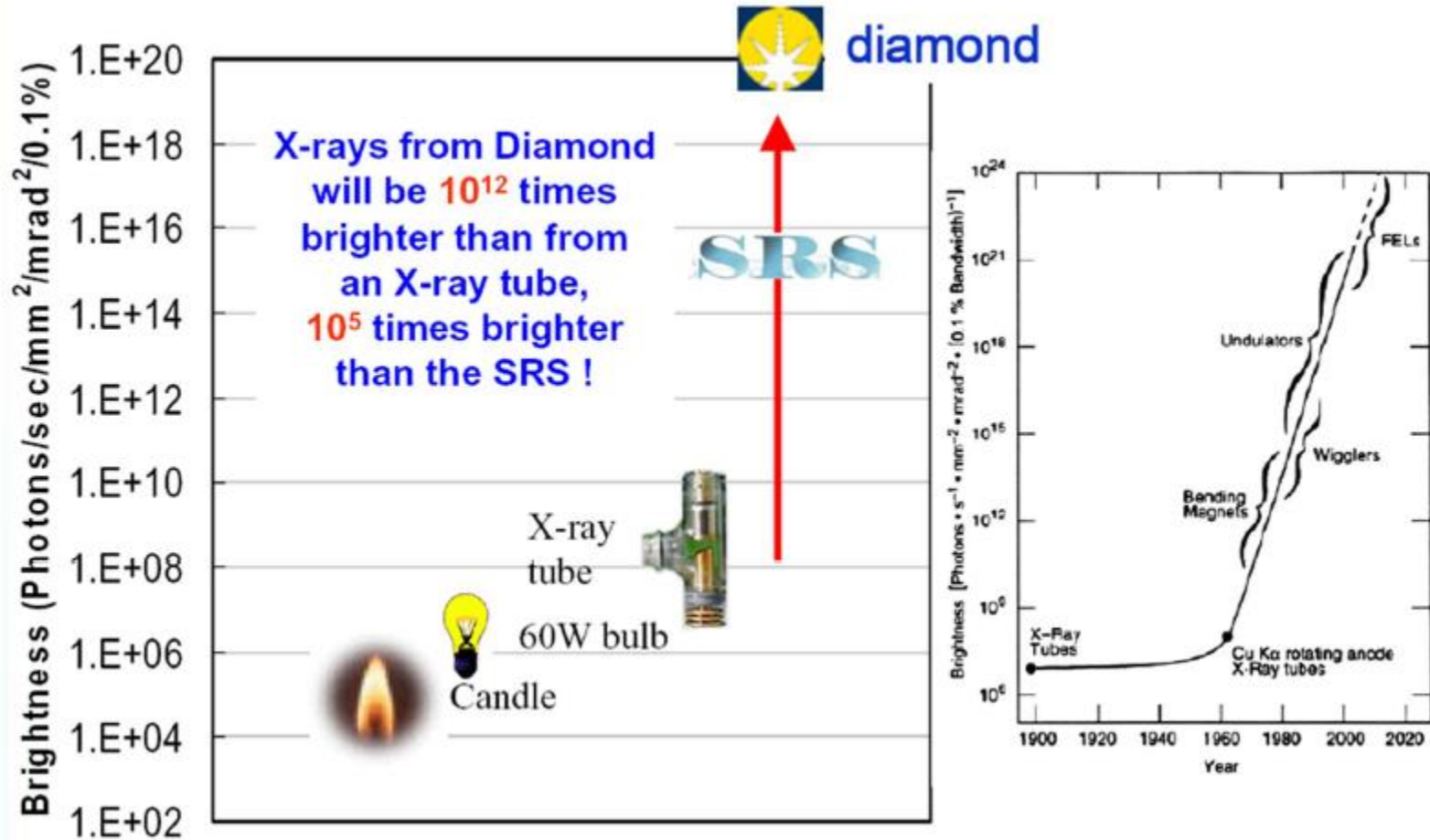
- ✦ However: $\int \frac{ds}{c} = 2\pi \int \frac{d\rho}{c}$

Lepton energy

- ✦ Finally, this gives: $u = \frac{4\pi}{3} \frac{r}{(m_0 c^2)^3} E^4 \int \frac{1}{\rho^2} d\rho = -\frac{CE^4}{\rho}$

Gets very large if E is large !!!

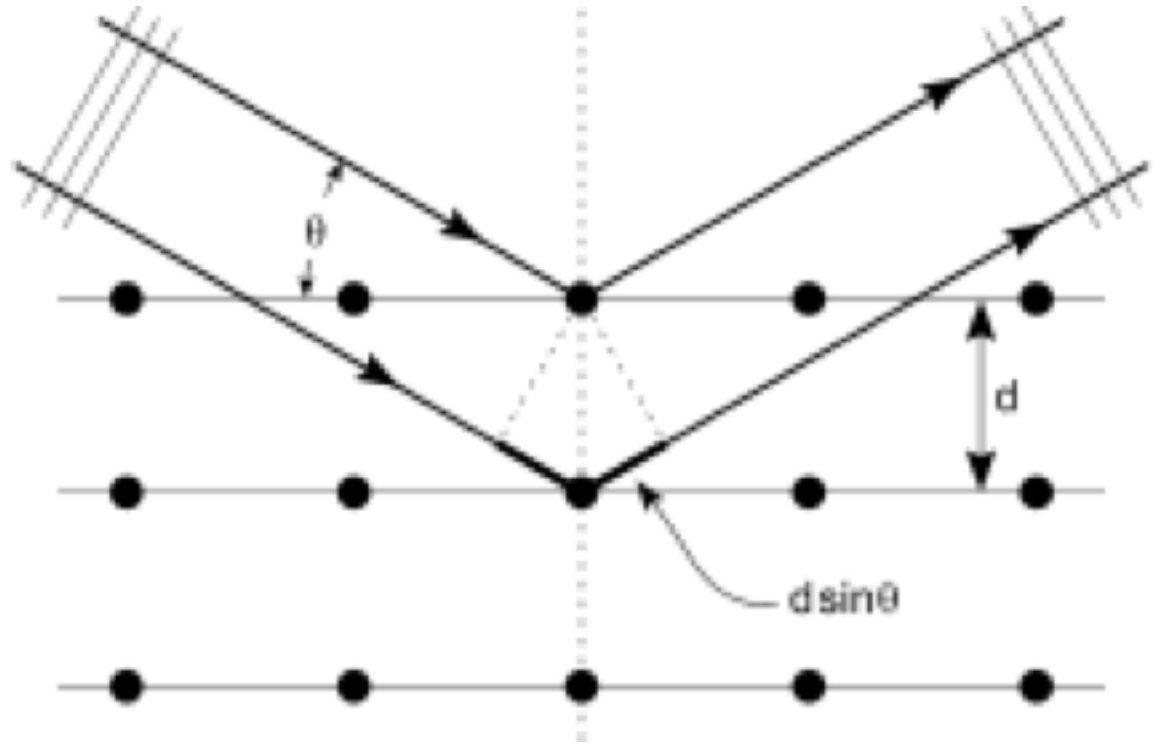
Accelerators for Synchrotron Light



X-ray Diffraction

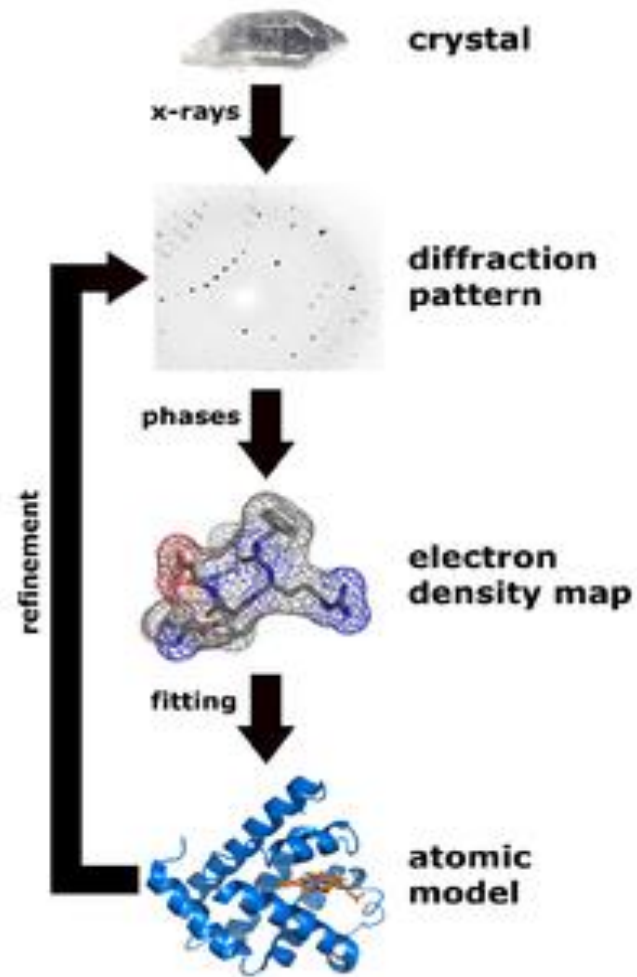


Max von Laue
1914 Nobel Prize:
'For his discovery of the
diffraction of X-rays
by crystals'



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

X-ray Diffraction Today

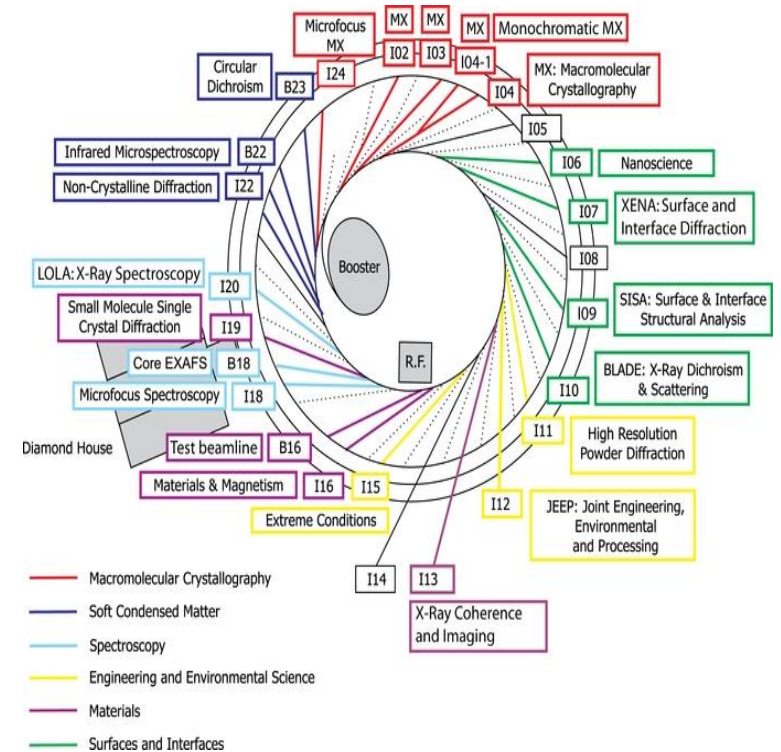


Diamond Light Source



Diamond Light Source, Harwell Science and Innovation Campus, UK

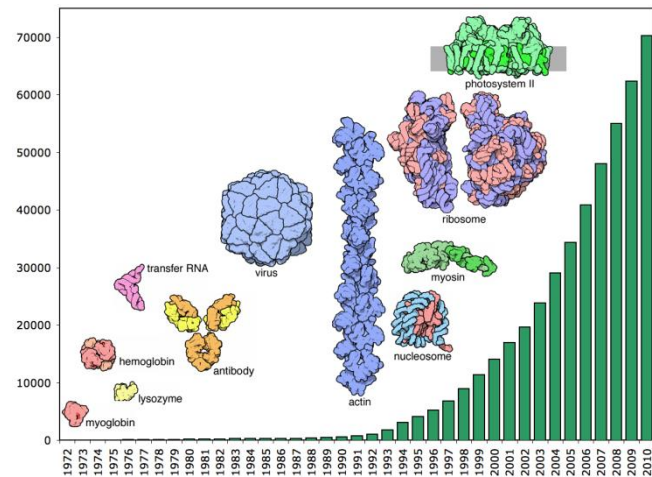
Diamond Light Source Beamlines



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

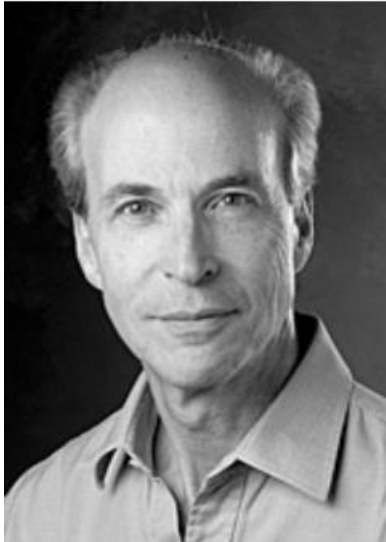


*The trimer of the Lassa nucleoprotein,
part of the Lassa virus*



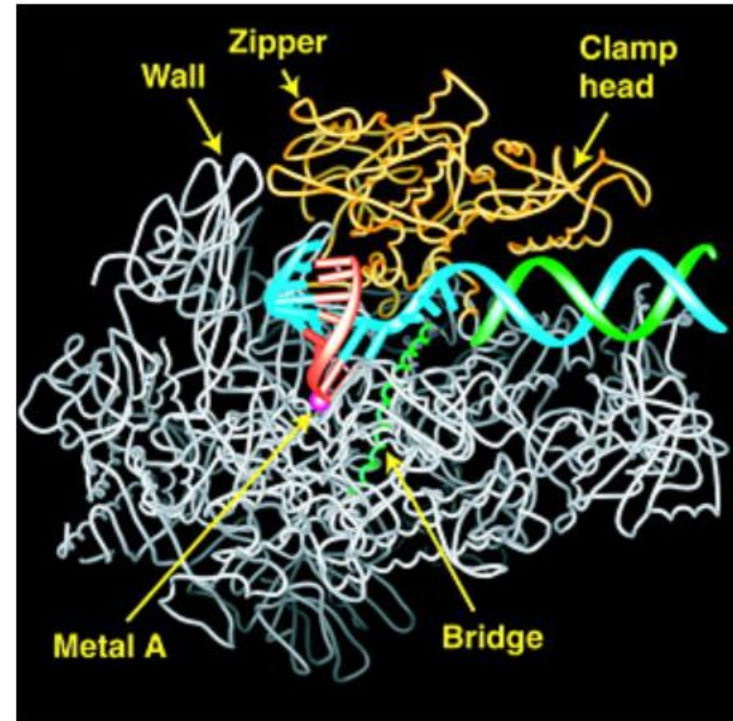
The Nobel Prize in Chemistry 2006

Roger D. Kornberg



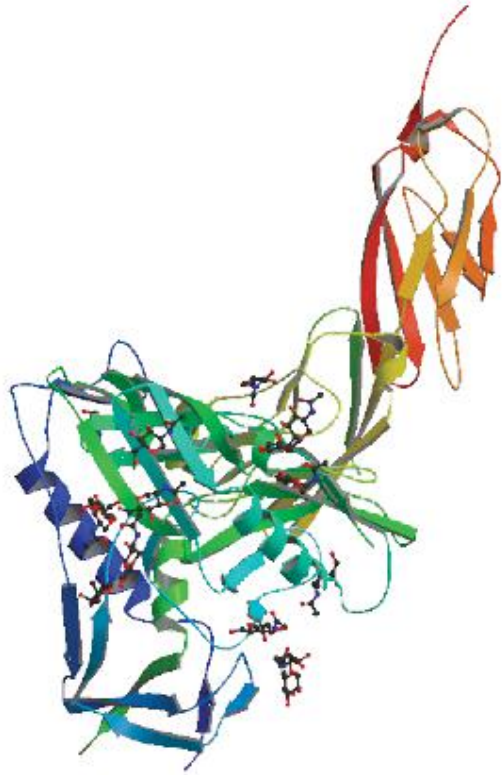
Roger Kornberg's Nobel Prize-winning determination of the structure of RNA polymerase has been described as a “technical tour de force.” The key to the visualization of this fundamental biological molecule in action was synchrotron radiation, supplied by the powerful X-ray crystallography instruments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

Science

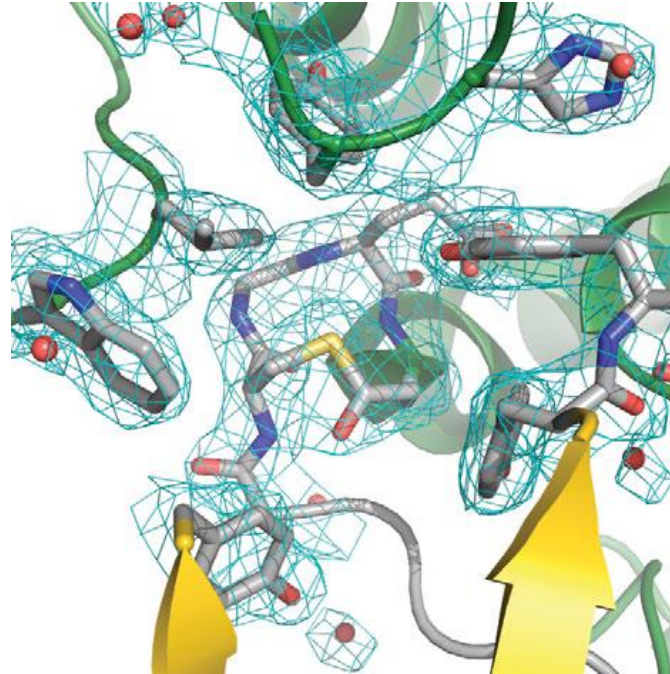


The transcription process visualized by Roger Kornberg and his colleagues in his X-ray crystallography studies published online April 19, 2001, in *Science*. The protein chain shown in grey is RNA polymerase, with the portion that clamps on the DNA shaded in yellow. The DNA helix being unwound and transcribed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

Protein Structure Revealed by Light Sources



HIV glycoprotein

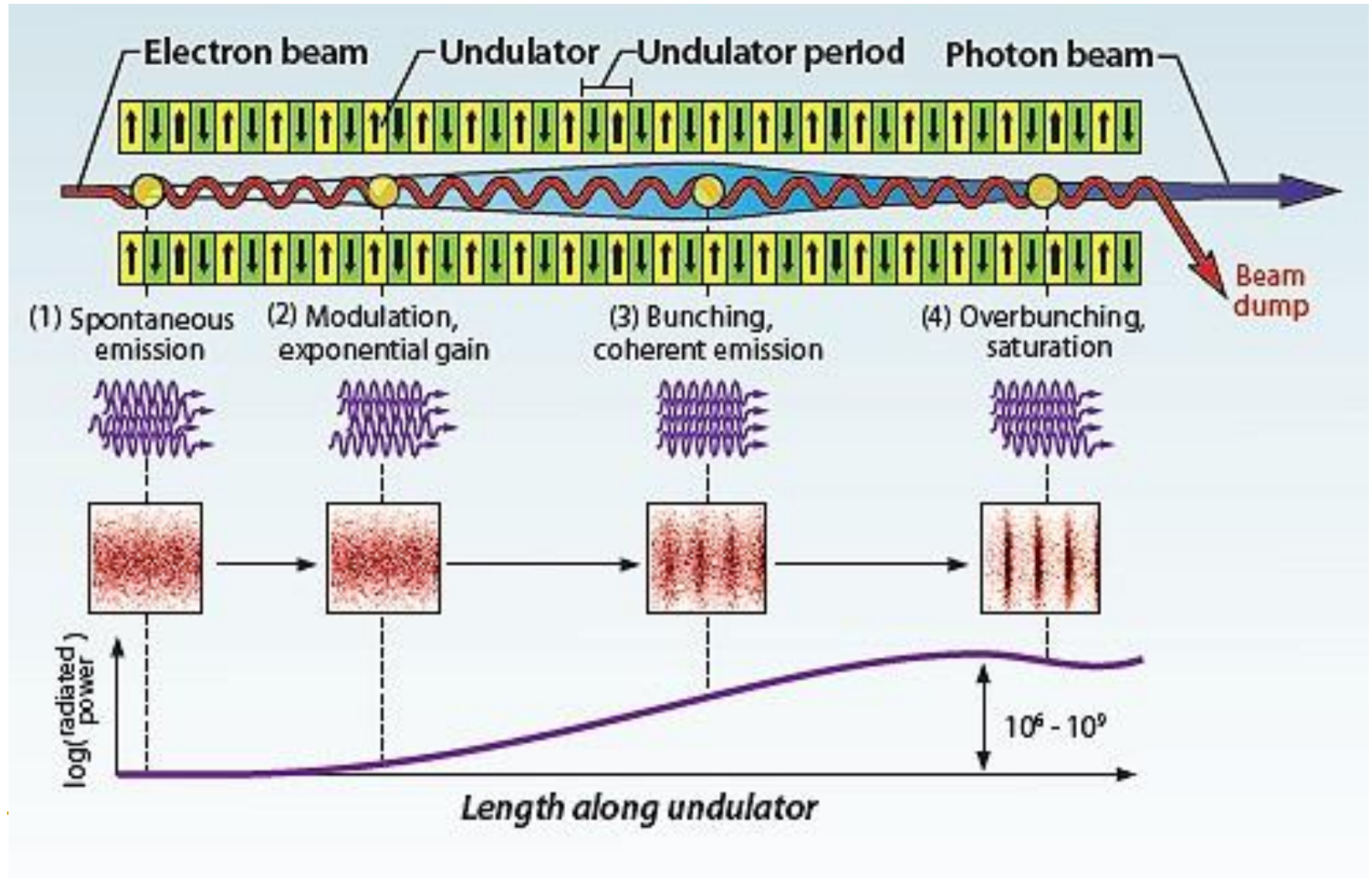


mosquito
immune system



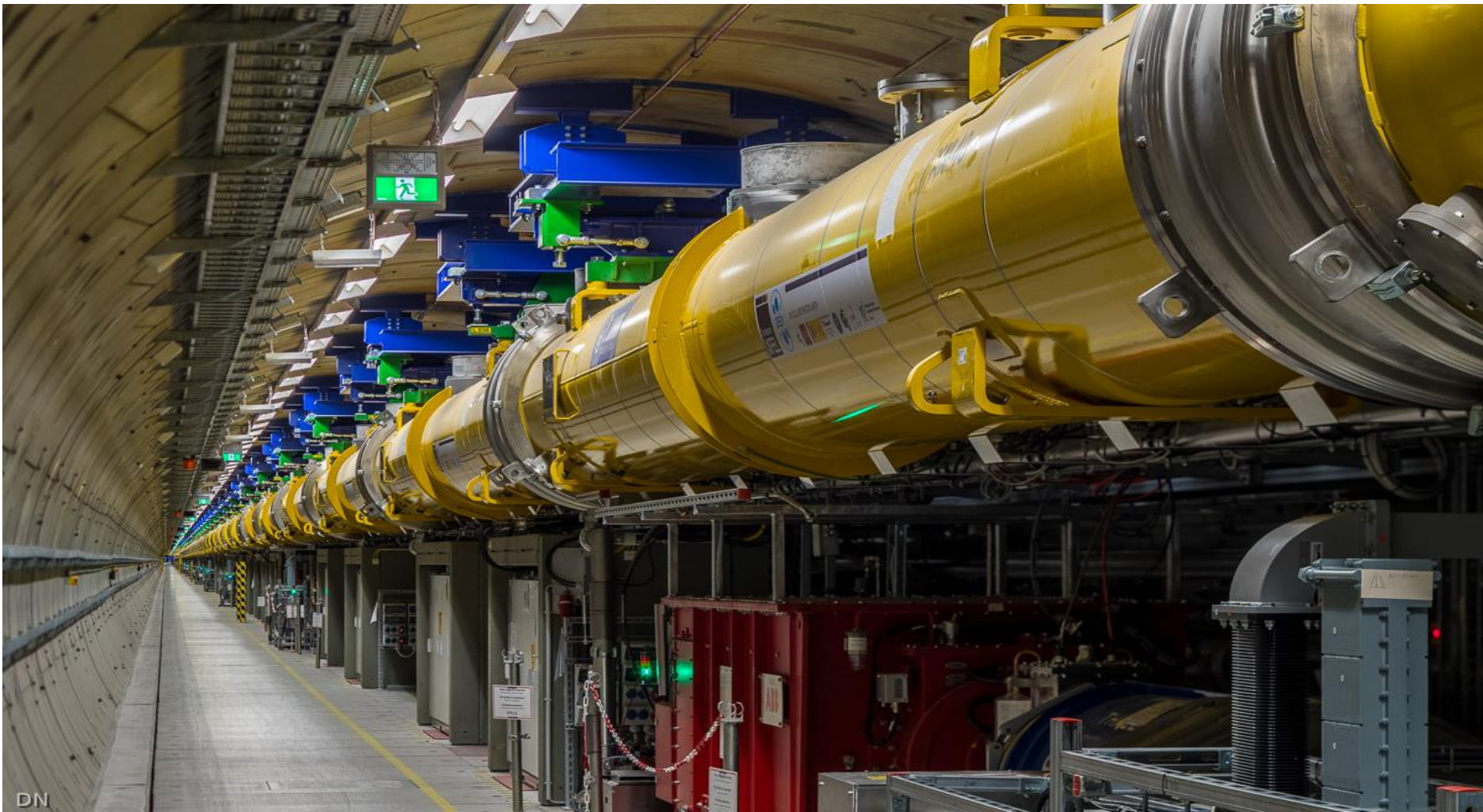
yeast enzyme

4th Generation Light Source – Free Electron Laser



European XFEL

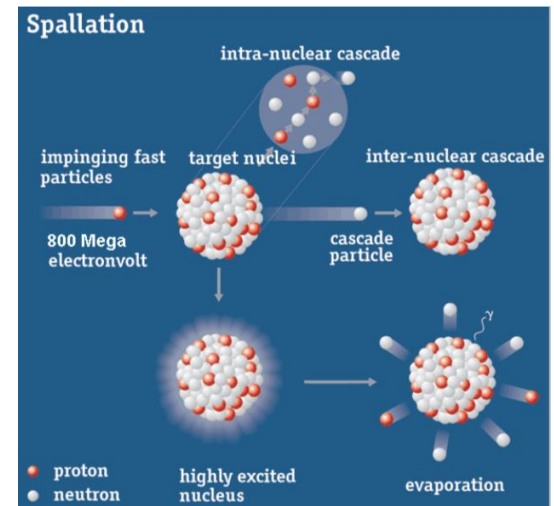
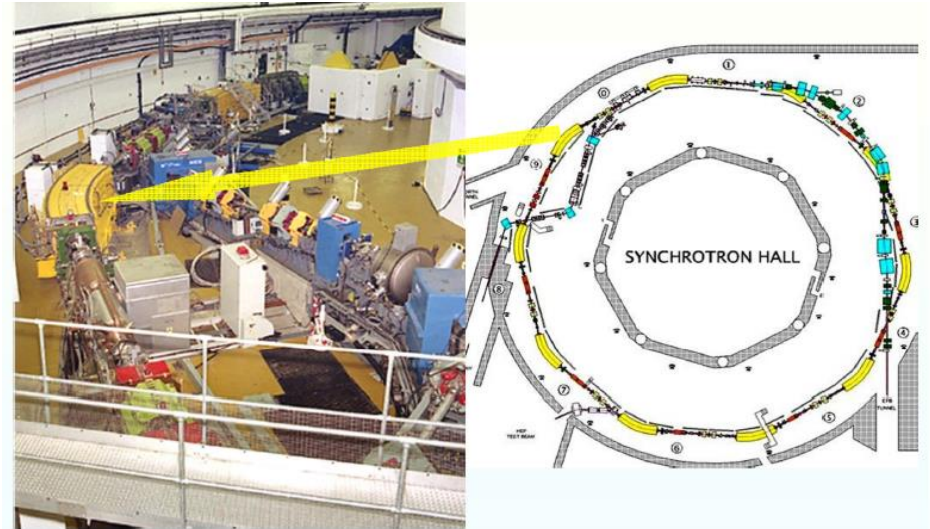
- **European XFEL at DESY is a large-scale proto-type for the ILC**
 - **100 cryomodules; 23.6 MV/m, accelerator length 2.1 km; 17.5 GeV**
 - **Successfully started operation in 2017**



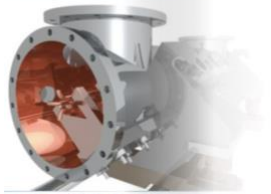
Accelerators for Neutron Science

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



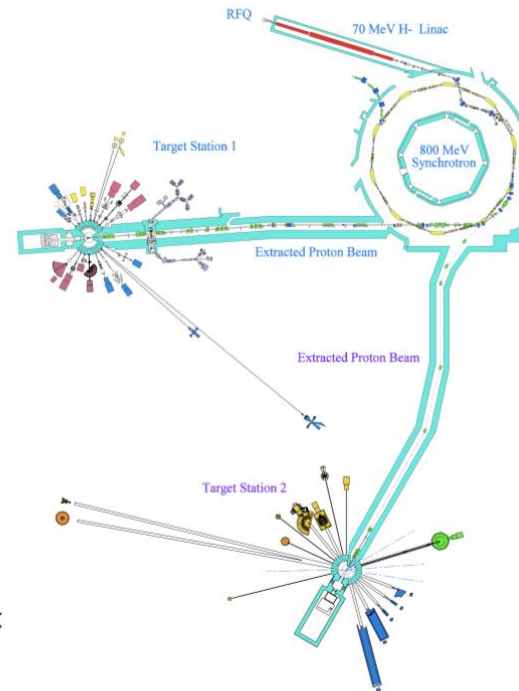
ISIS Accelerators and Targets

- 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 μA (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).

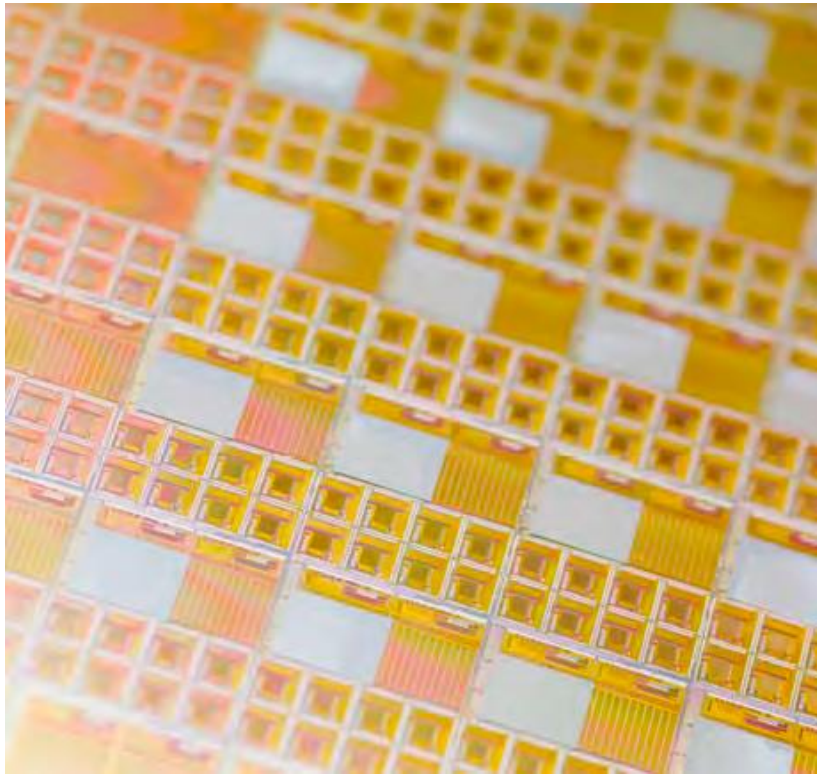
$$P = 800[MV] \times 230[\mu A] = 184[kW]$$



Accelerators for Ion Beam Implantation

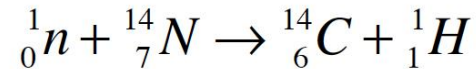
- Ion implantation in semiconductor manufacture
- Typical semiconductor fabrication:
140 operations, 70 involving ion
implantation at specific sites in crystal
- Ions accelerated to modest energies
Depth of implant controlled by ion beam energy:
typically 2 → 600 keV

Ion Beam Implantation Products

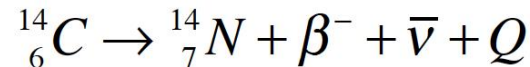


Radiocarbon ^{14}C Formation & Decay

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



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

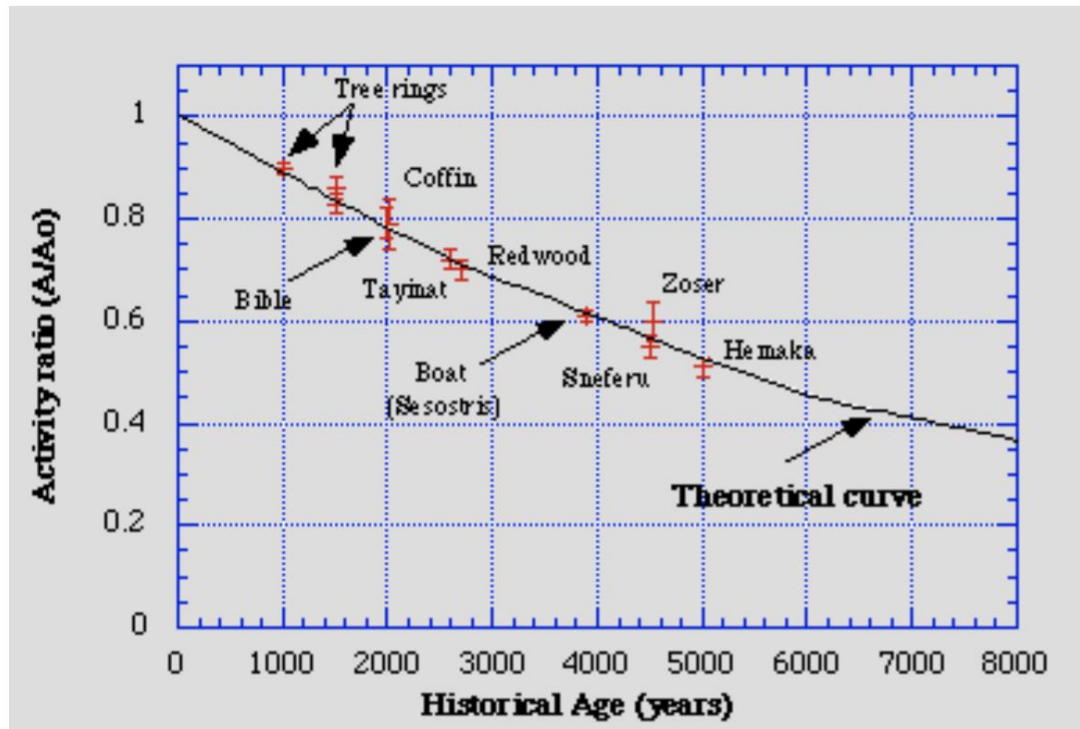


Radiocarbon dating was first explored by W.R. Libby (1946), who later won the Nobel Prize.

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.



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

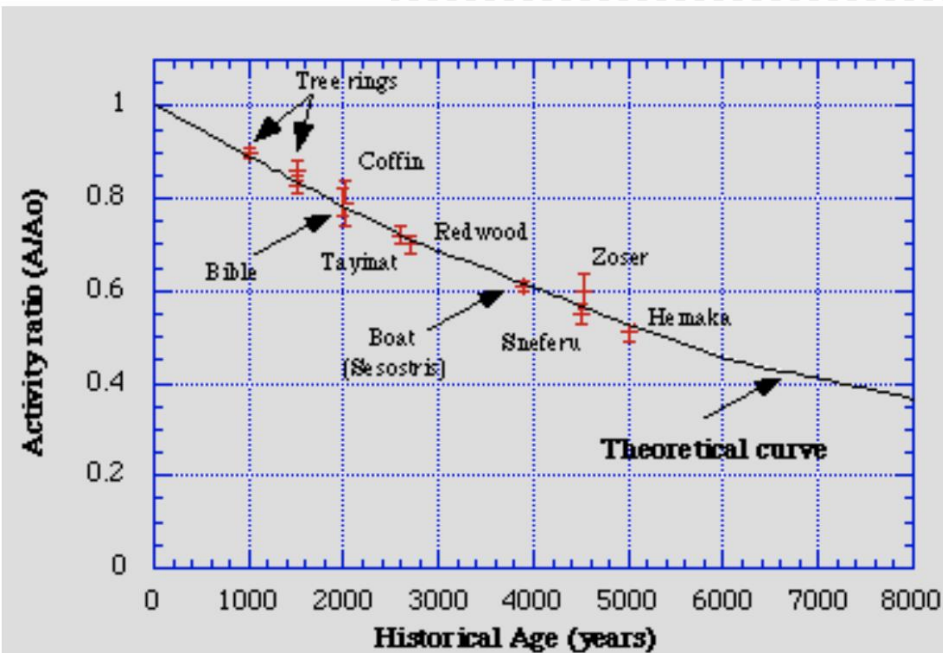
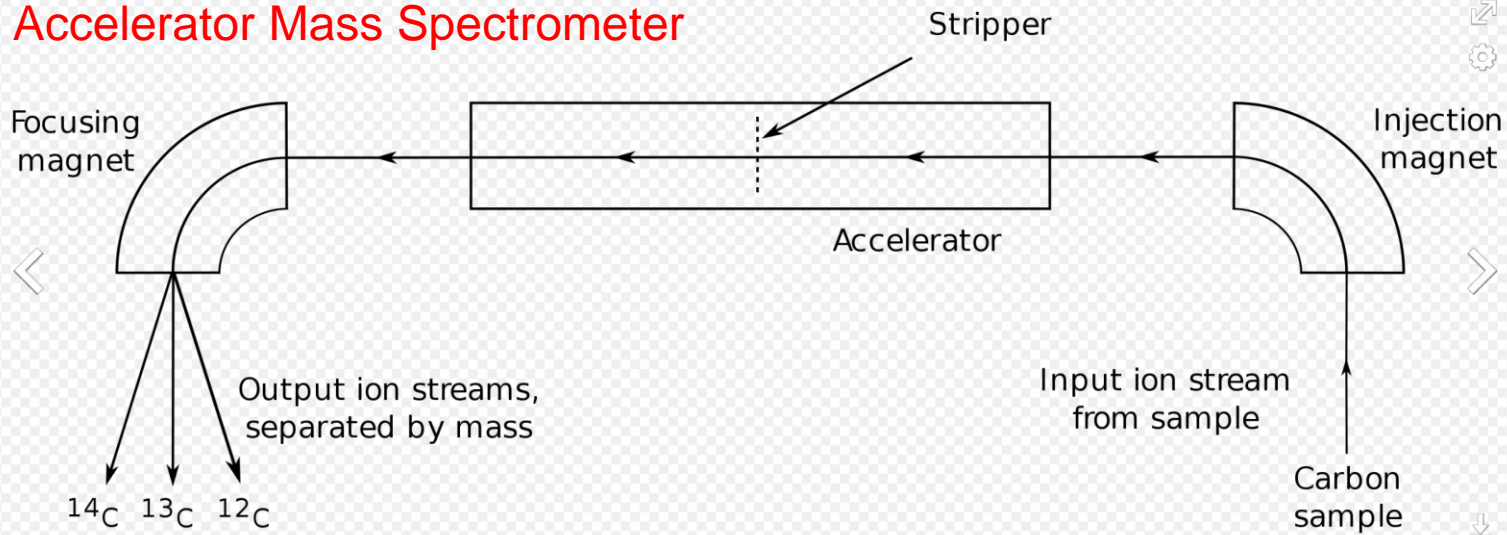
where present-day, pre-bomb,
 ^{14}C activity = 13.56dpm/g C



Accelerators for History & Culture Applications

Radiocarbon Dating

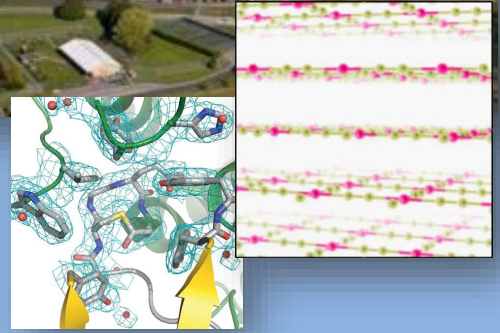
Accelerator Mass Spectrometer



PHYSICAL
REVIEW
LETTERS

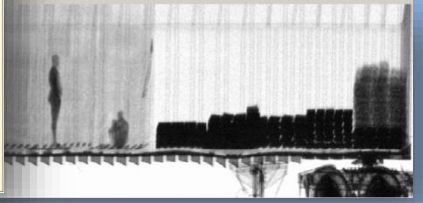
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Niels Bohr



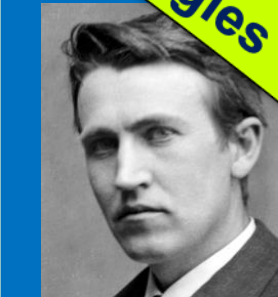
Louis Pasteur



Accelerator Science
and Technologies

PASTEUR'S
QUADRANT
Basic Science
and Technological
Innovation

Donald E. Stokes



Thomas Edison



Consideration of use

Fundamental knowledge

Bibliography

