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
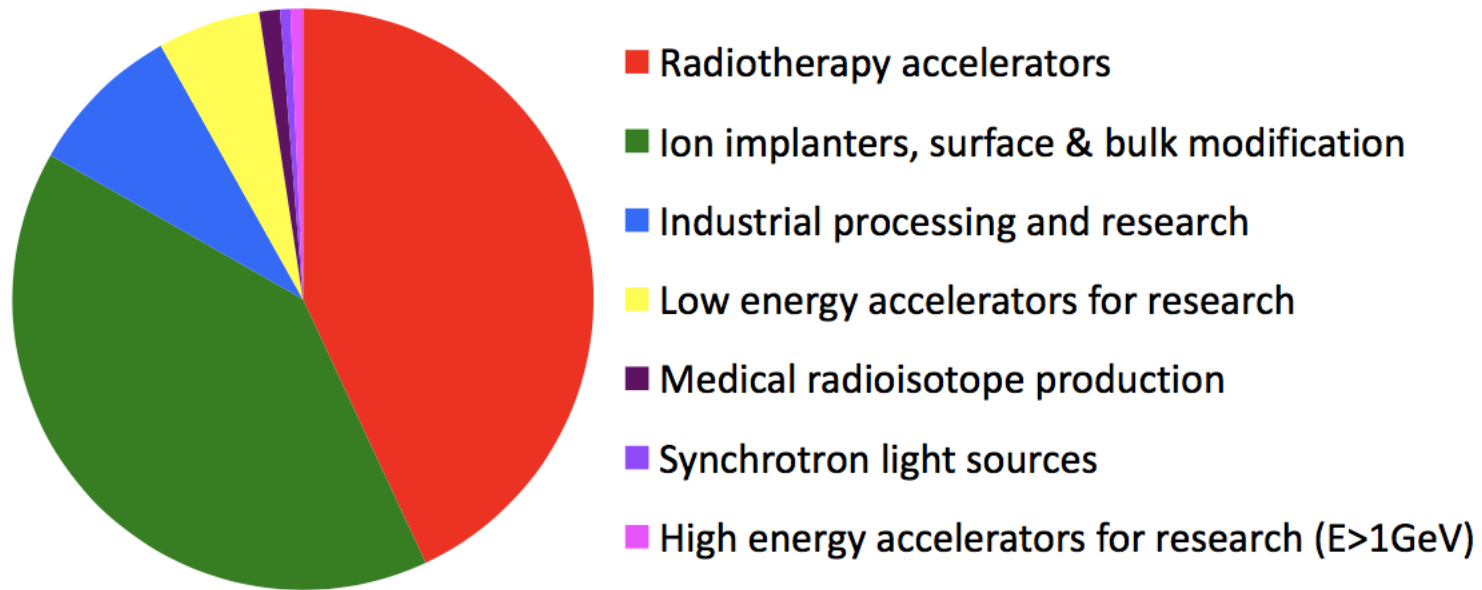
17 October 2019

Introduction

Accelerators Worldwide

- Radiotherapy accelerators
- Ion implanters, surface & bulk modification
- Industrial processing and research
- Low energy accelerators for research
- Medical radioisotope production
- Synchrotron light sources
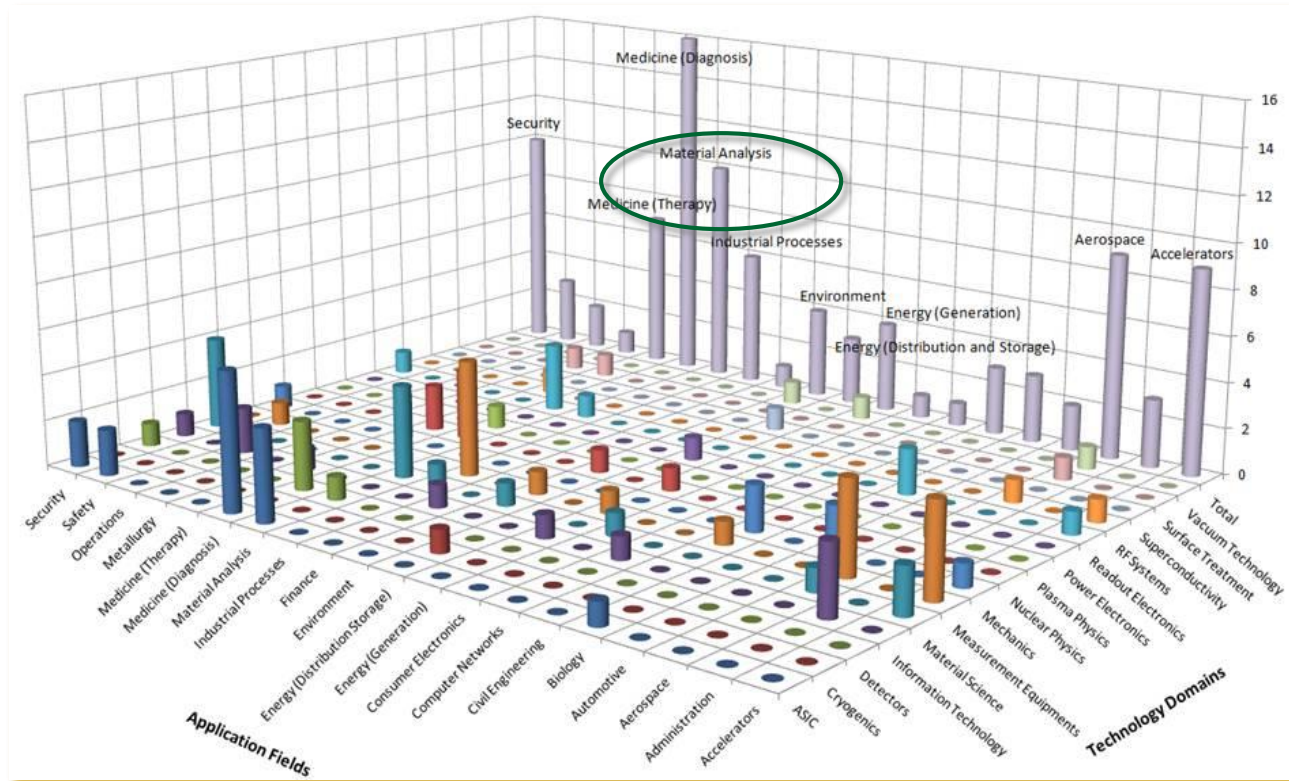- High energy accelerators for research (E>1GeV)

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

Accelerators are not only for particle physics
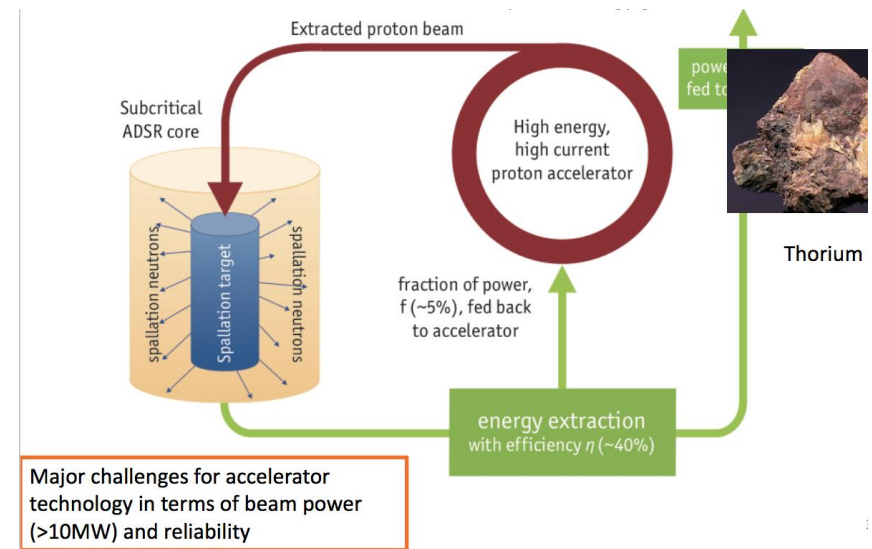
Accelerator Technologies and Innovation

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 (ADSR)**
  - 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.

Thorium

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

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.
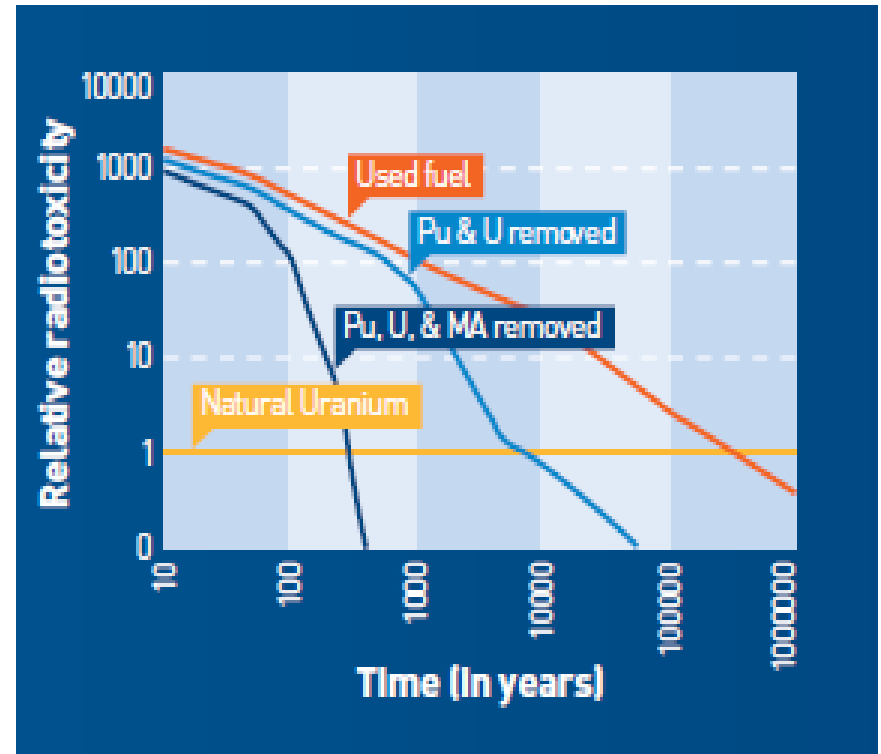
Accelerators for Energy

- 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.
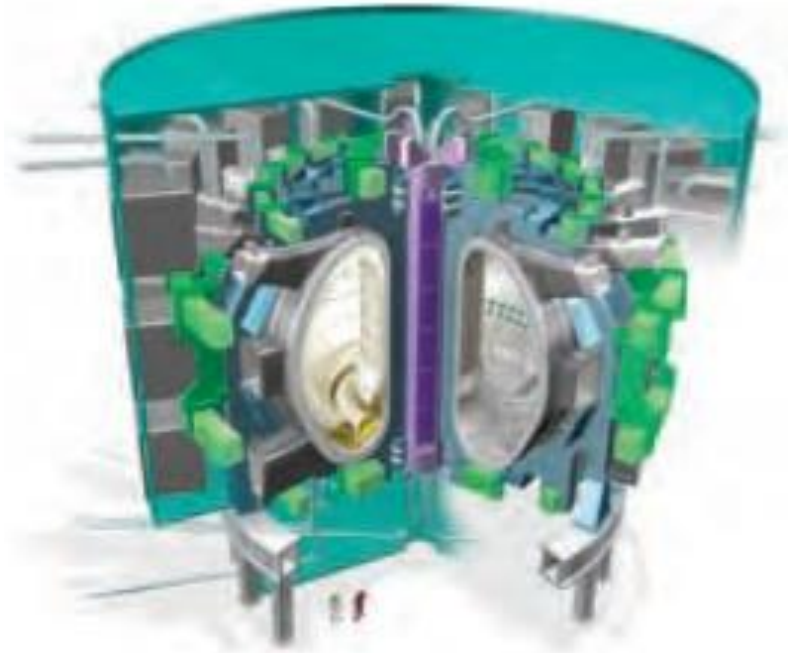
Accelerators for the Environment

- **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

Image source: Varian medical systems
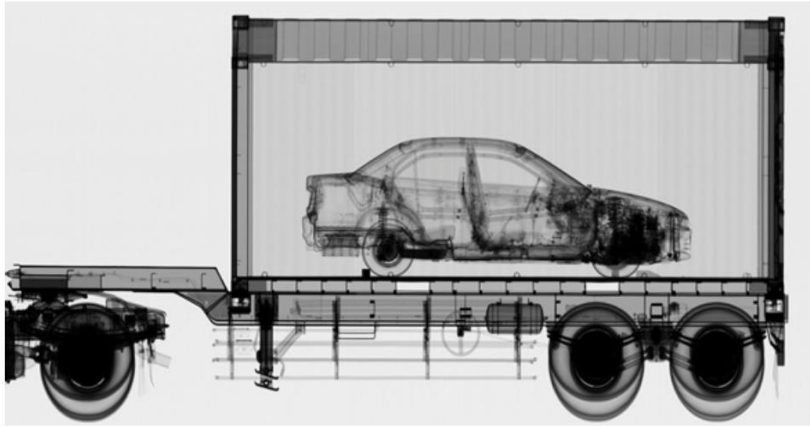
Cargo containers scanned at ports and border crossings

Accelerator-based sources of X-Rays can be far more penetrating (6MV) than Co-60 sources.
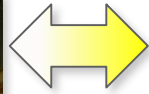
Container must be scanned in 30 seconds.
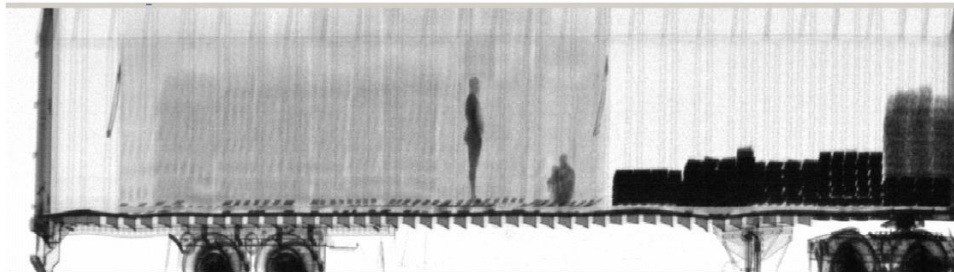
Image: dutch.euro

Accelerators for Medicine

Combining Physics, ICT, Biology and Medicine to fight cancer

Accelerating particle beams
~35'000 accelerators worldwide
~17'000 used for medicine

Hadron Therapy
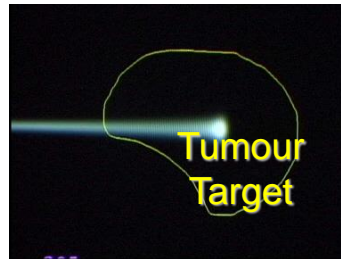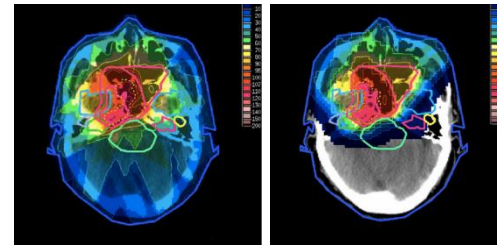
Protons
light ions

X-ray   protons

Leadership in Ion Beam Therapy now in Europe and Japan

>100'000 patients treated worldwide (45 facilities)
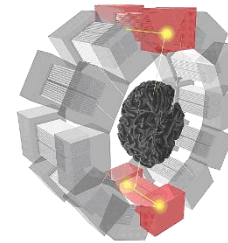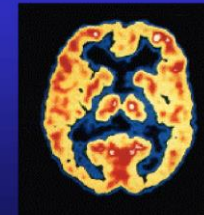>50'000 patients treated in Europe (14 facilities)
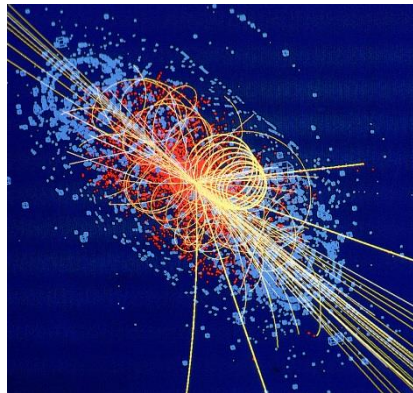
Imaging

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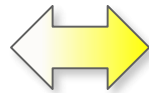
Clinical trial in Portugal, France and Italy for new breast imaging system (ClearPEM)
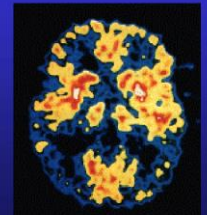

PET Scanner

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.

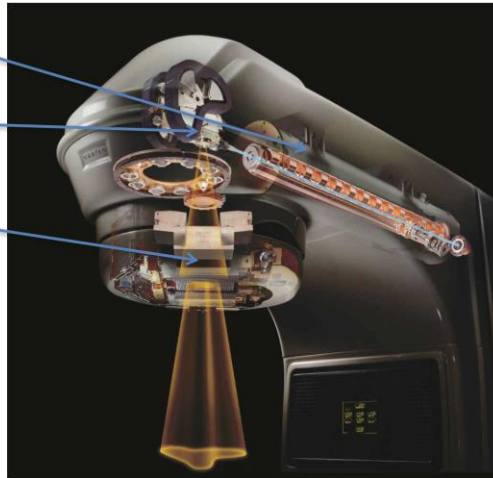
Linac

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 12C-ions

Loma Linda Proton Treatment Centre Constructed at FNAL
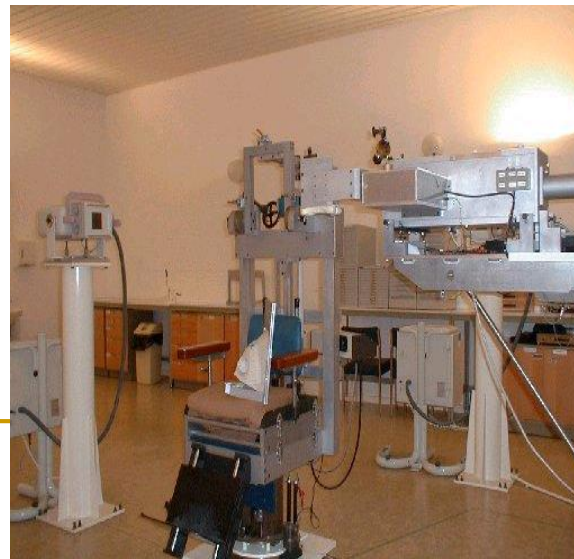
Established 1989
60 MeV protons
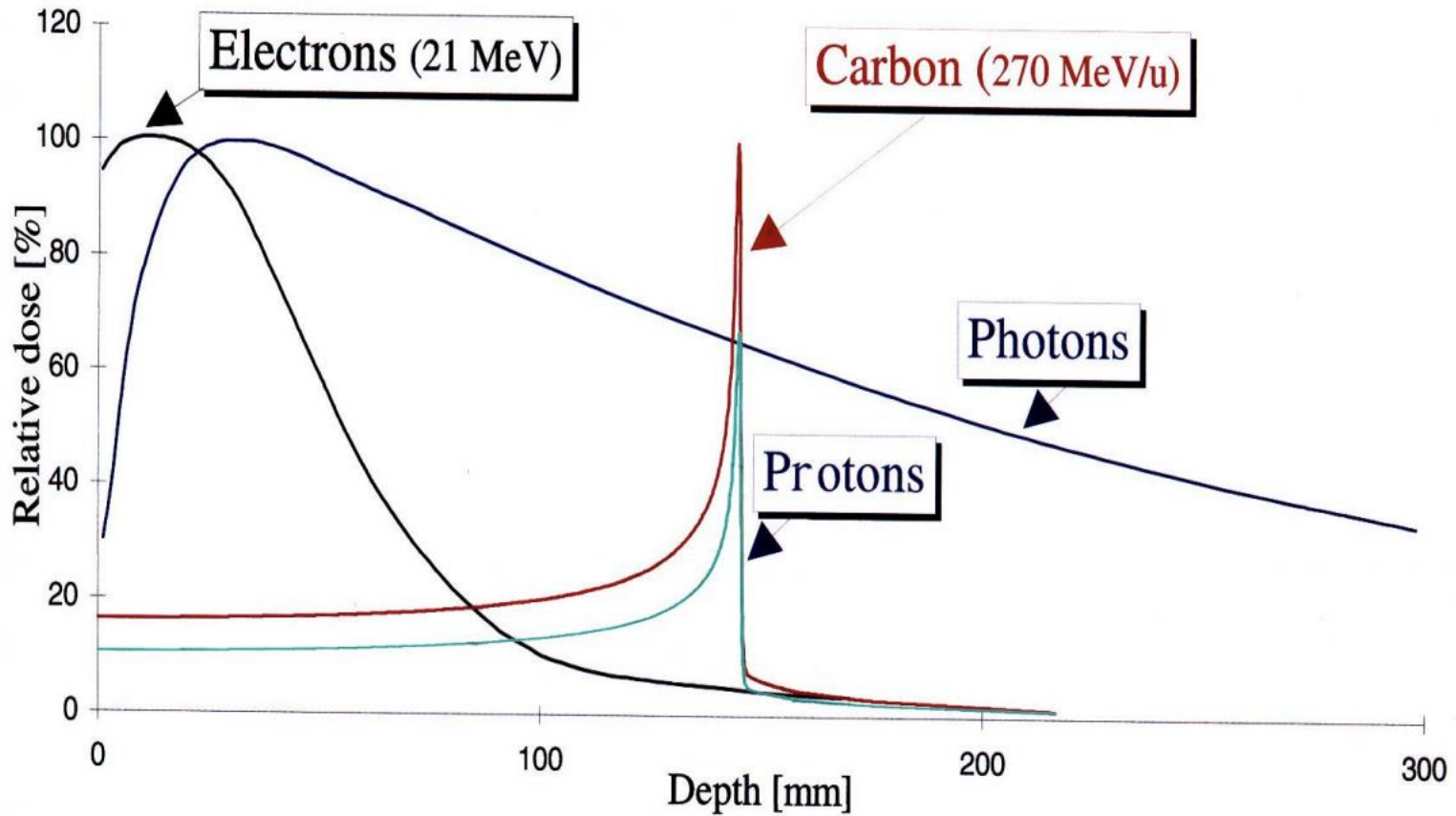
First hospital-based proton therapy

PIMMS @ CERN

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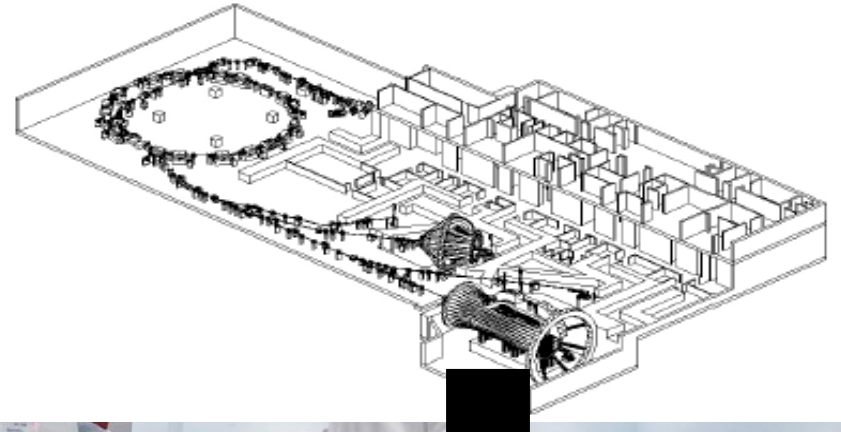
PIMMS (Proton-Ion Medical Machine Study) based at CERN
Members: CERN, TERA, Med-AUSTRON, collaboration with GSI.
Technical Design Report in 2000, CD-ROM of data and drawings.

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

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

- ◆ dE/dx in [MeV g⁻¹ cm²]

- ◆ valid for "heavy" particles ($m \geq m_\mu$).

- ◆ 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

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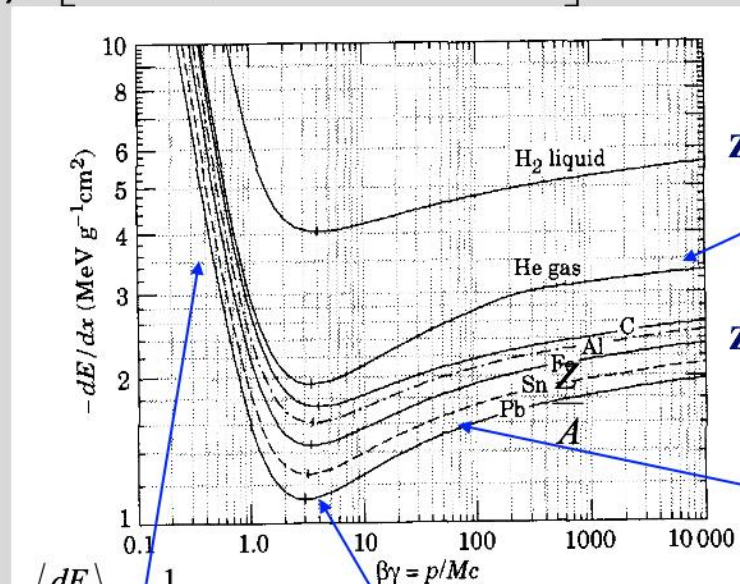
"relativistic rise"

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

"kinematical term"

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

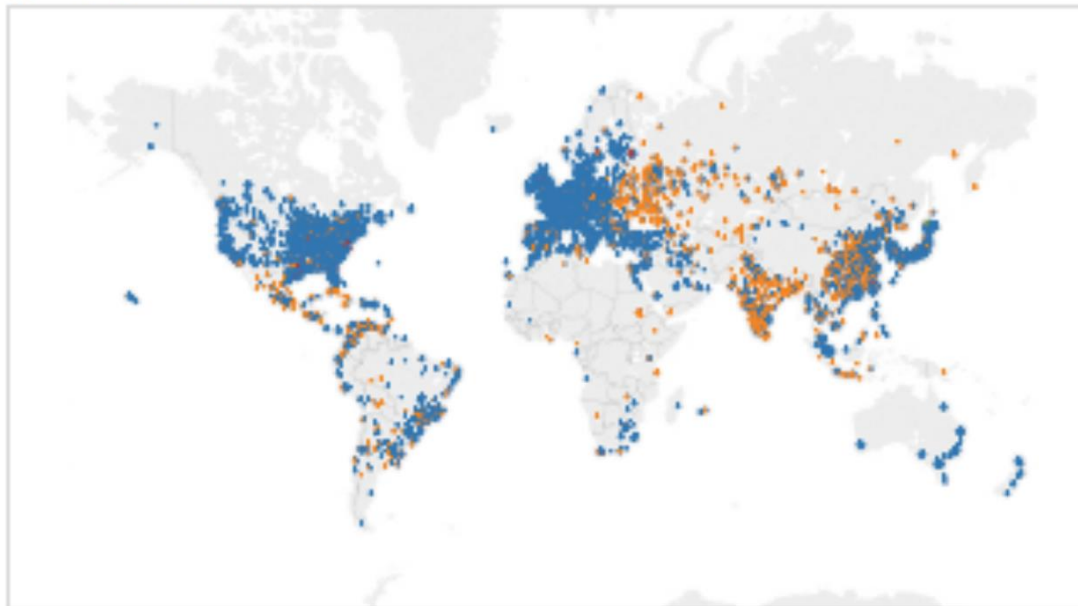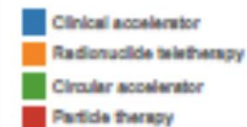# World-wide Radiotherapy Coverage

Radiation therapy centers
(Updated on : 6/1/2017 7:11:24 AM)

Equipment type
(Updated on : 6/1/2017 7:11:24 AM)

| Equipment	Count
Clinical accelerator	11,440
Radionuclide teletherapy	2,186
Particle therapy	115
Circular accelerator	14

Income groups

Group	Count
High income (H)	8,202
Upper middle income (UM)	2,888
Lower middle income (LM)	
Low income (L)	
Temporarily unclassified (NC)	1

Legend:
- Clinical accelerator
- Radionuclide teletherapy
- Circular accelerator
- Particle therapy

Countries	RT centers	Equipment	Linac	Radionuclide Therapy	Circular Accelerator	Particle Therapy
139	7041	13755	11440	2186	14	115

World-wide Particle Therapy Centres

ENLIGHT © June 2018

FUNCTIONAL CENTERS   UNDER CONSTRUCTION
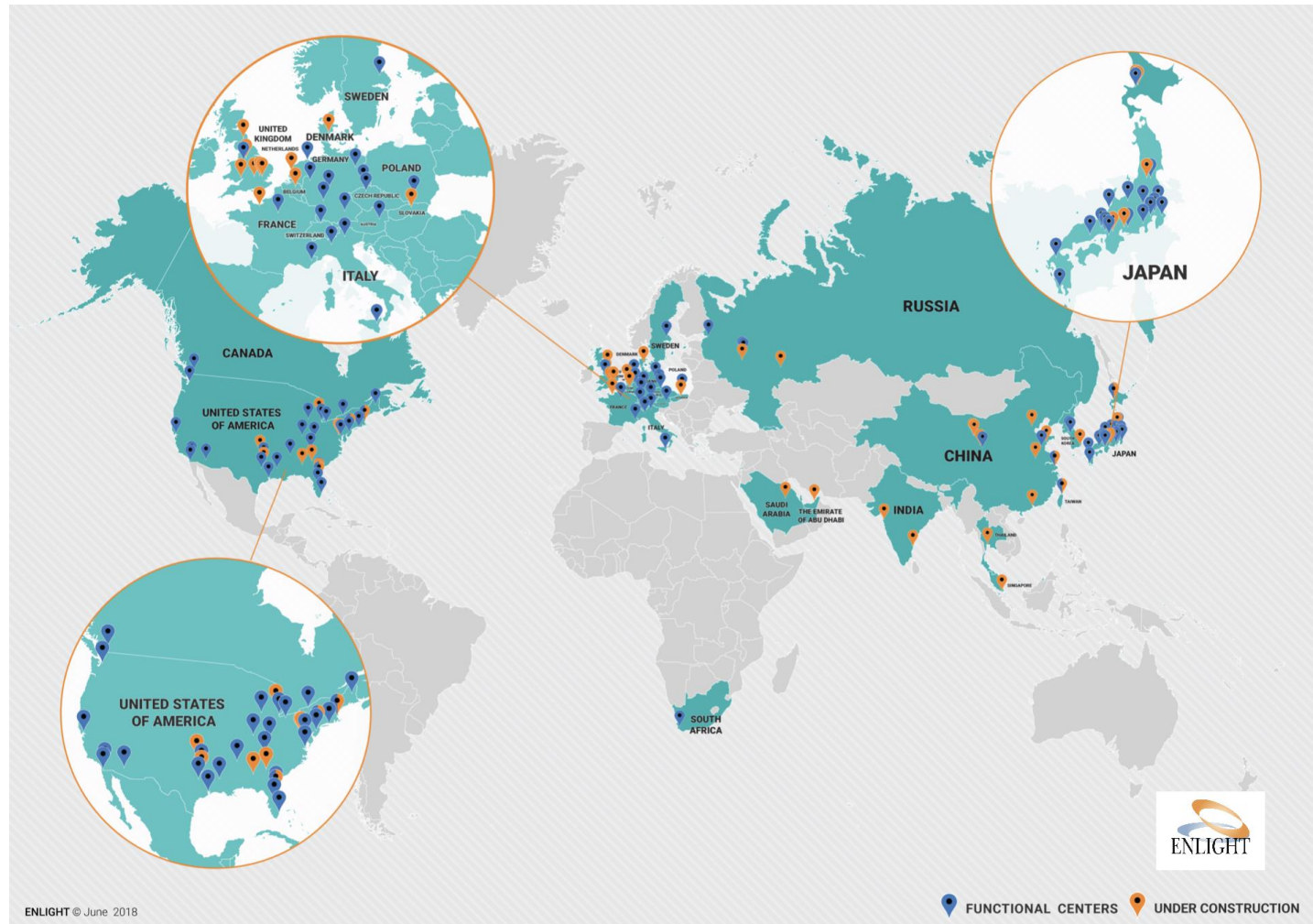
Particle Therapy Centres and Patients World-wide
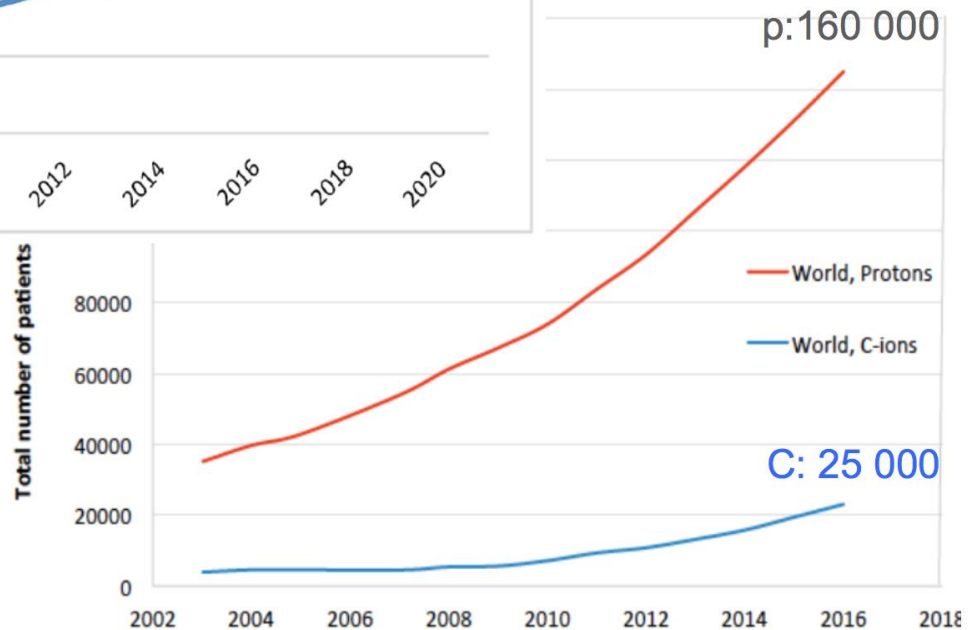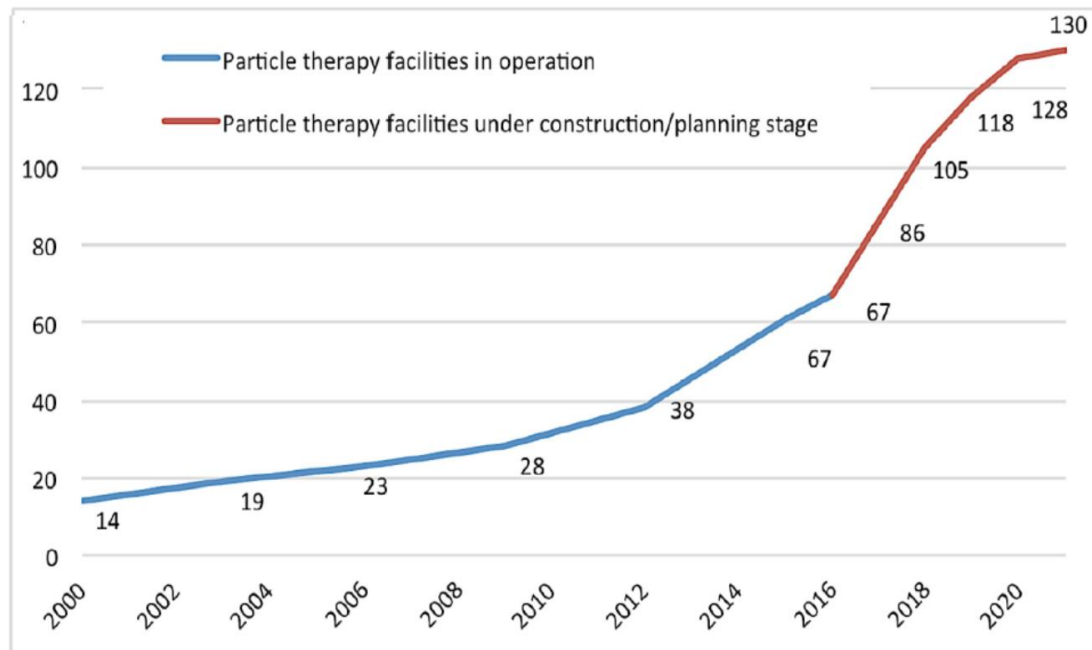

Manjit Dosanjh
JAI 2018

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
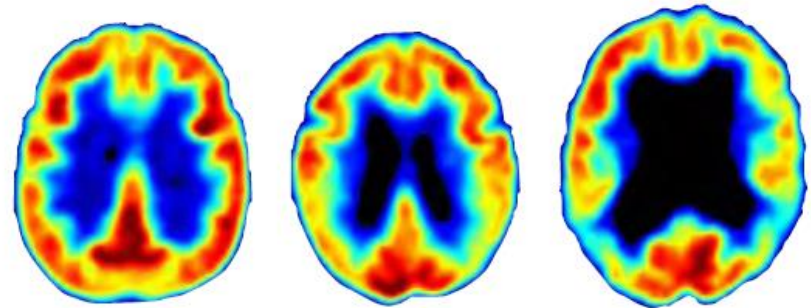
Normal   Mild cognitive Impairment   Alzheimer's disease

PET Scan

Neutrons & X-rays

Protein structure revealed with help of light sources
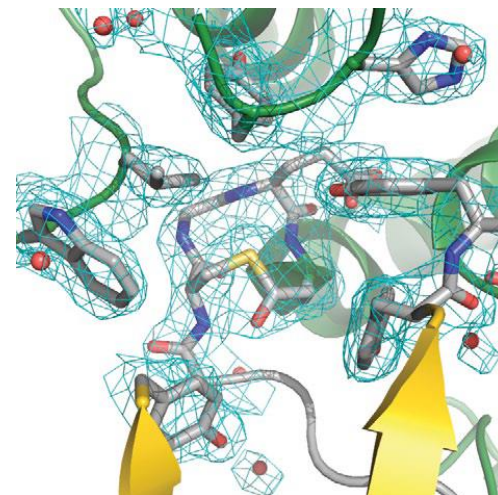
ISIS and Diamond neutron and X-ray sources
Harwell, UK

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

diamond

Science & Technology Facilities Council
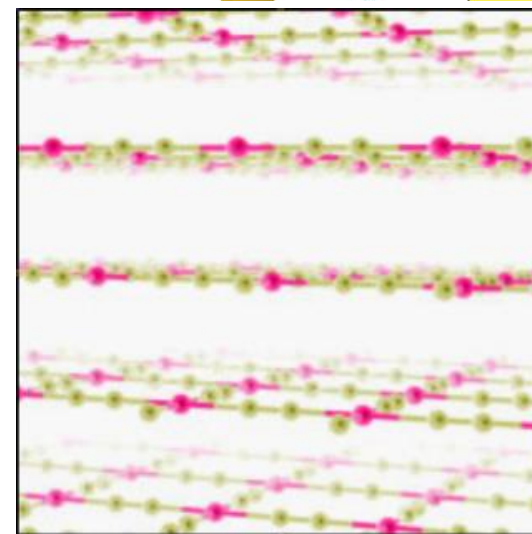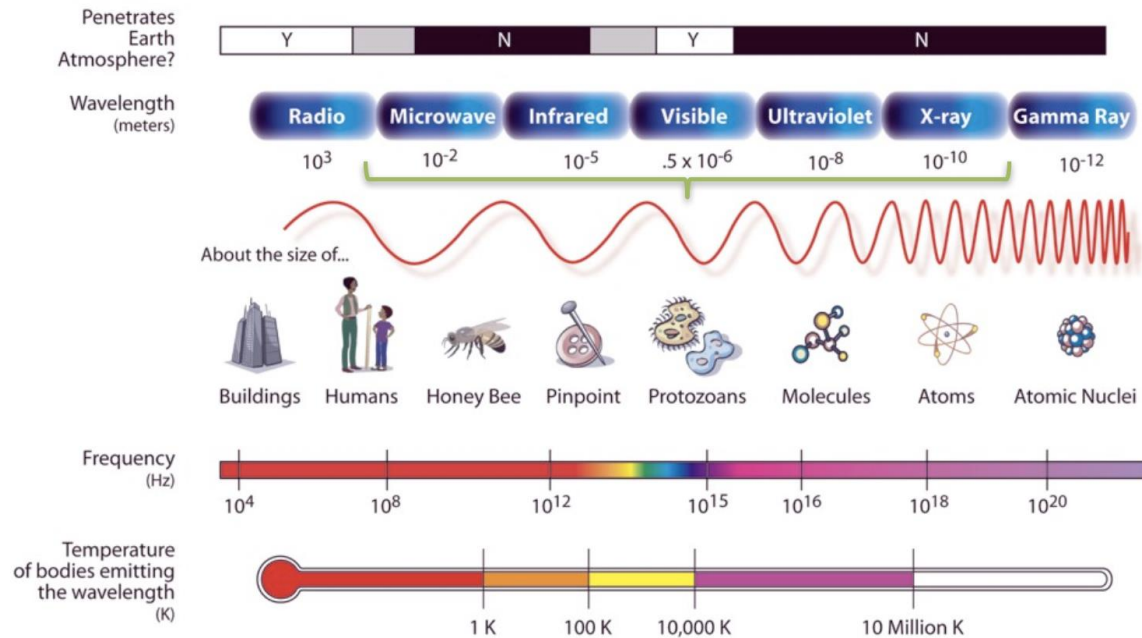
2-d material (graphene)

Synchrotron Light Sources

Courtesy ESRF

Synchrotron Light Sources

Synchrotron radiation is emitted by charged particles when accelerated radially
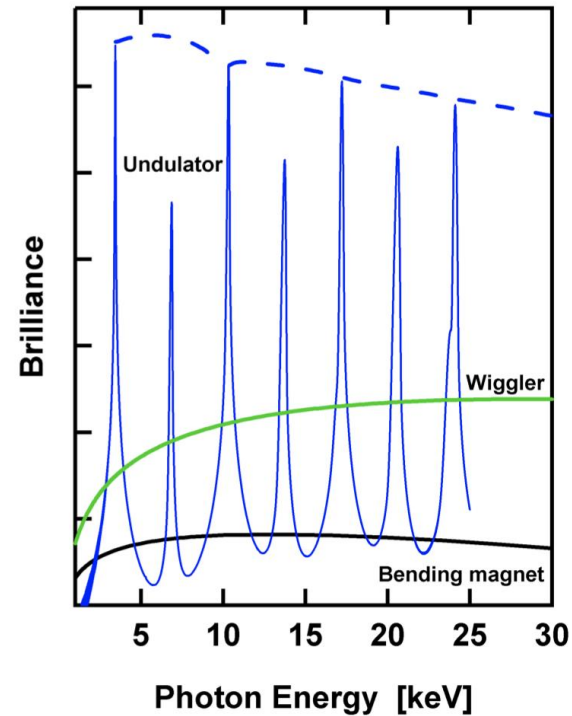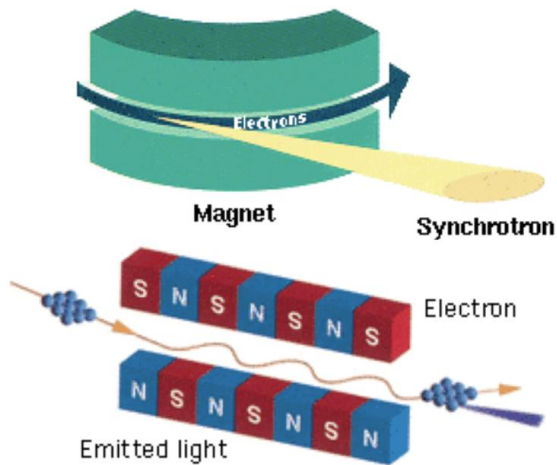
Produced in synchrotron radiation sources using bending magnets, undulators and wigglers

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
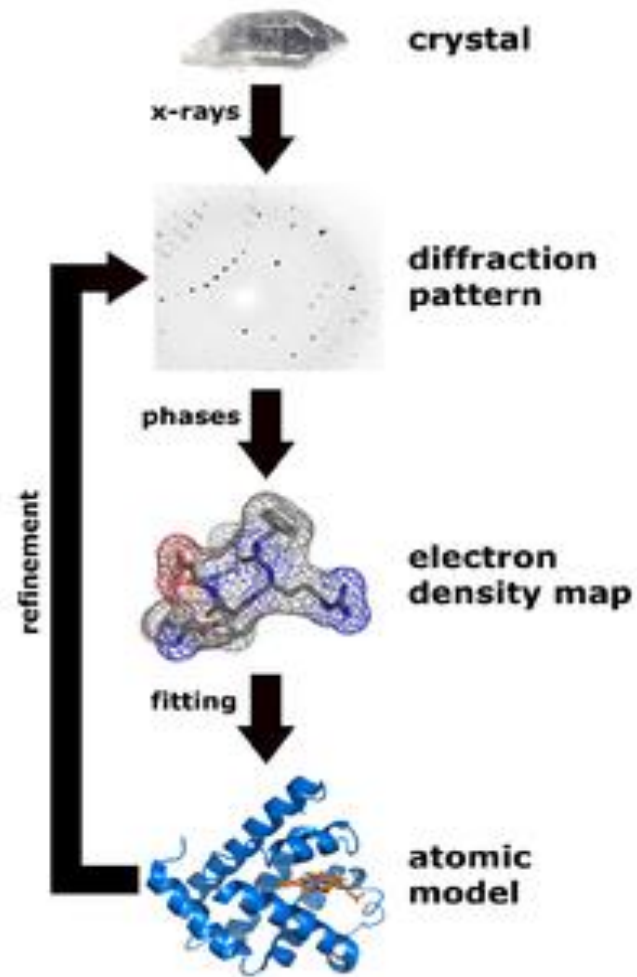
Accelerators for Synchrotron Light
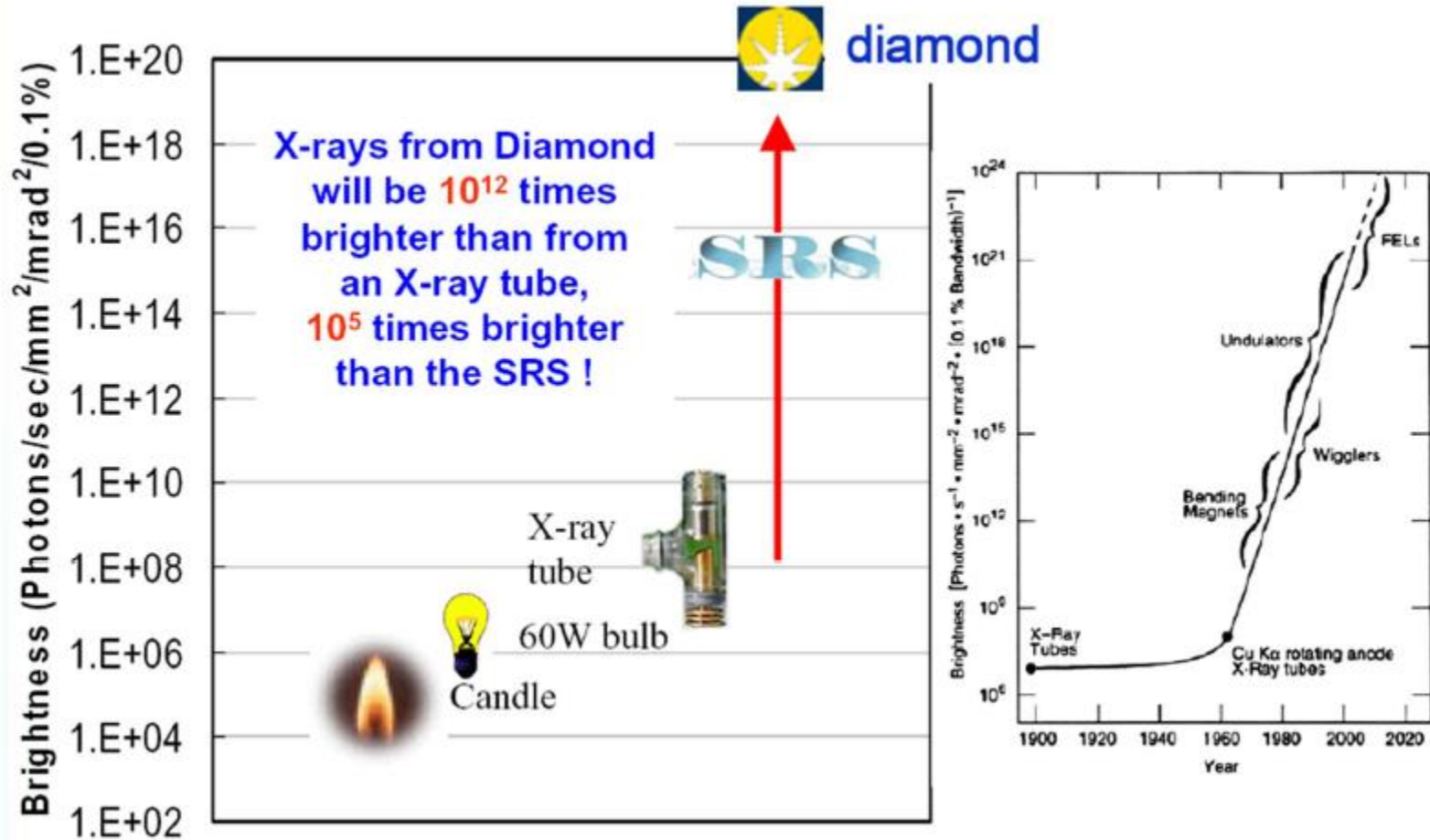
X-ray Diffraction

Max von Laue
1914 Nobel Prize:
'For his discovery of the
diffraction of X-rays
by crystals'
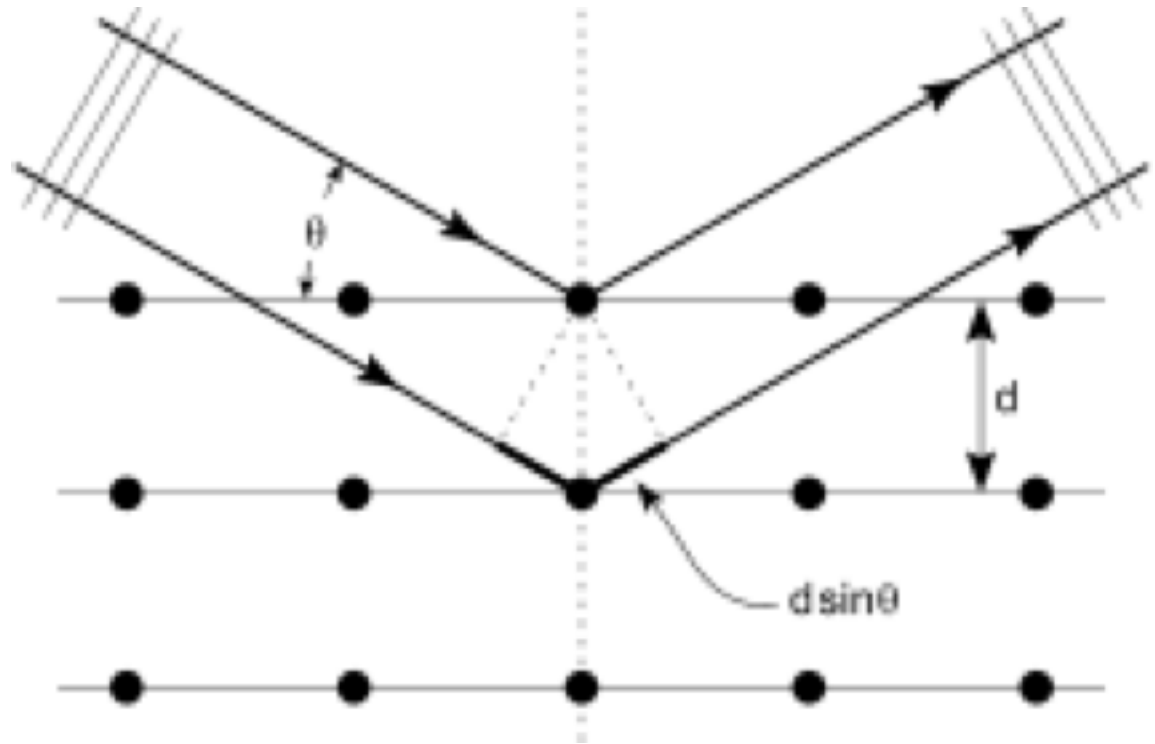
Constructive interference:
$$2\,d\,\sin\theta = n\,\lambda$$

X-ray Diffraction Today

Diamond Light Source

Diamond Light Source, Harwell
Science and Innovation Campus, UK

Diamond Light Source Beamlines
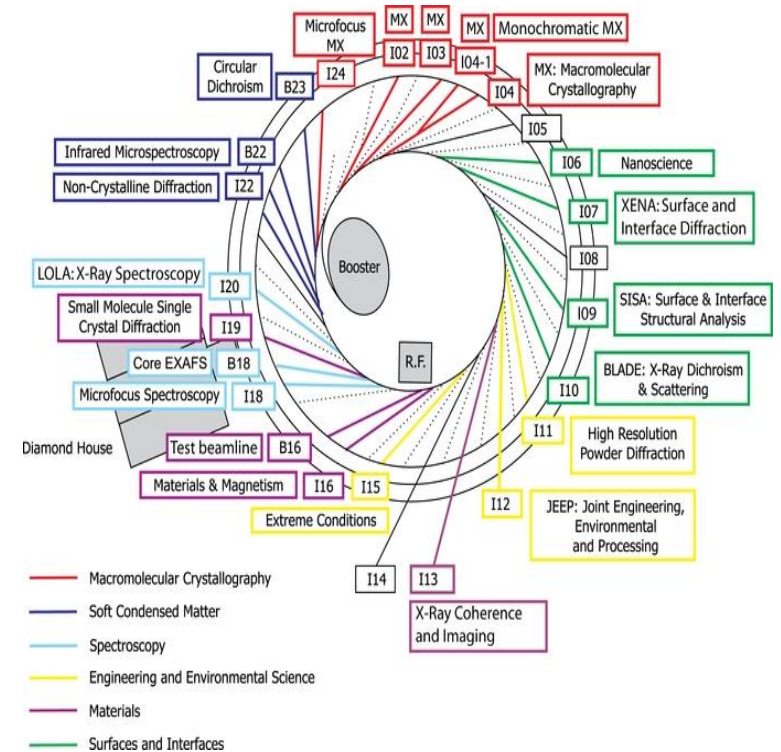
Accelerators for Synchrotron Light

- ## 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.
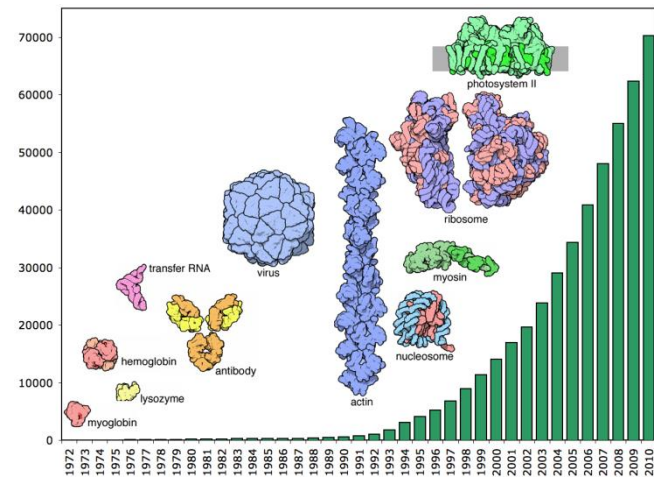
Protein Data Bank

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

The 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.

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.

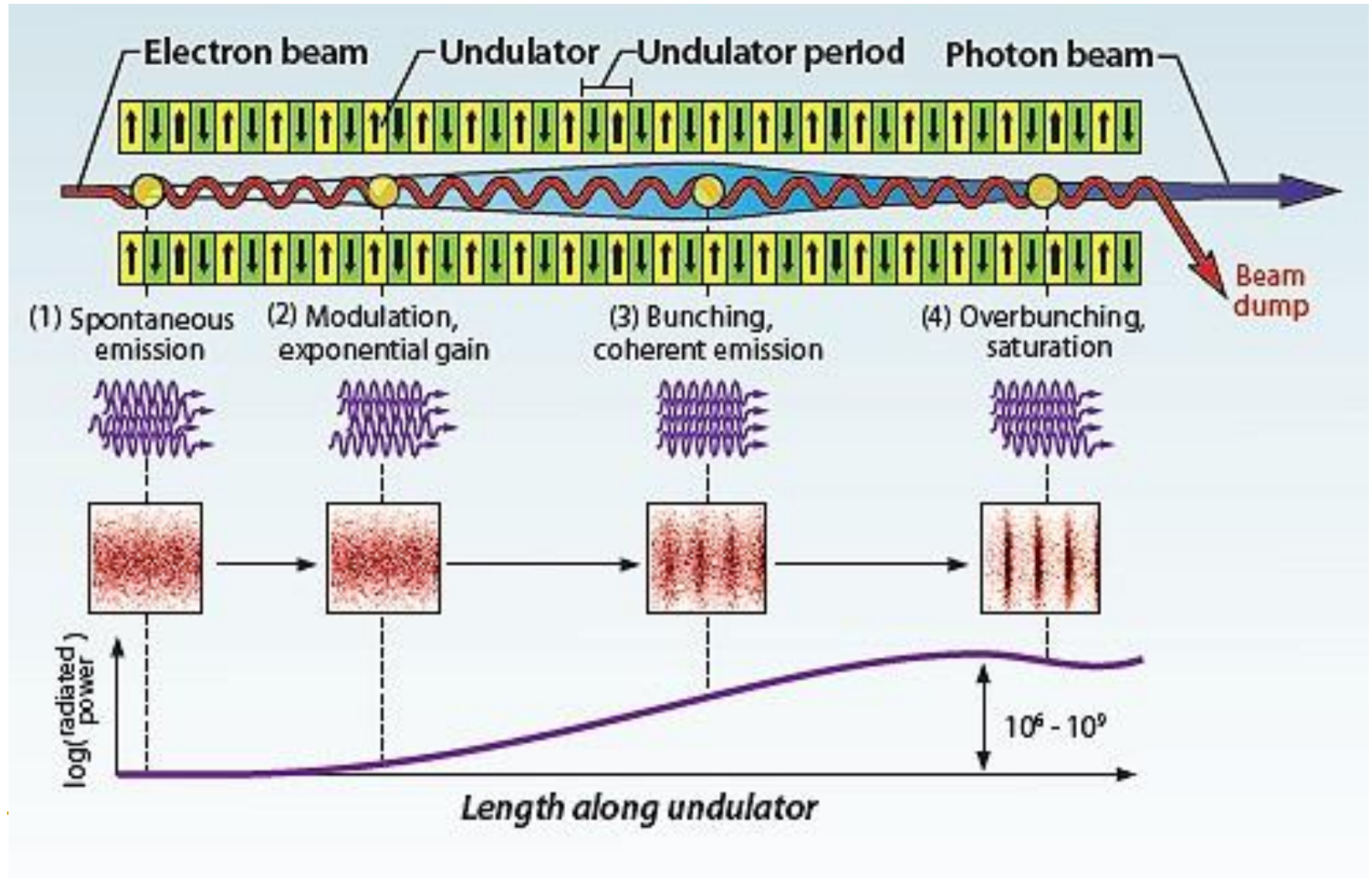# Protein Structure Revealed by Light Sources
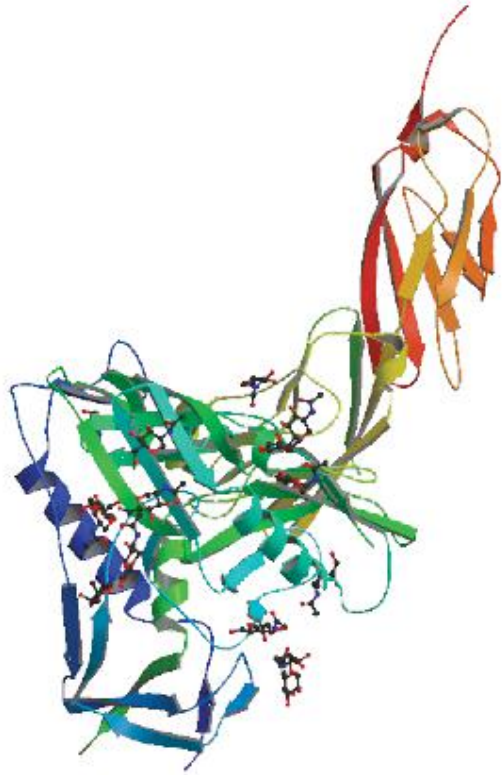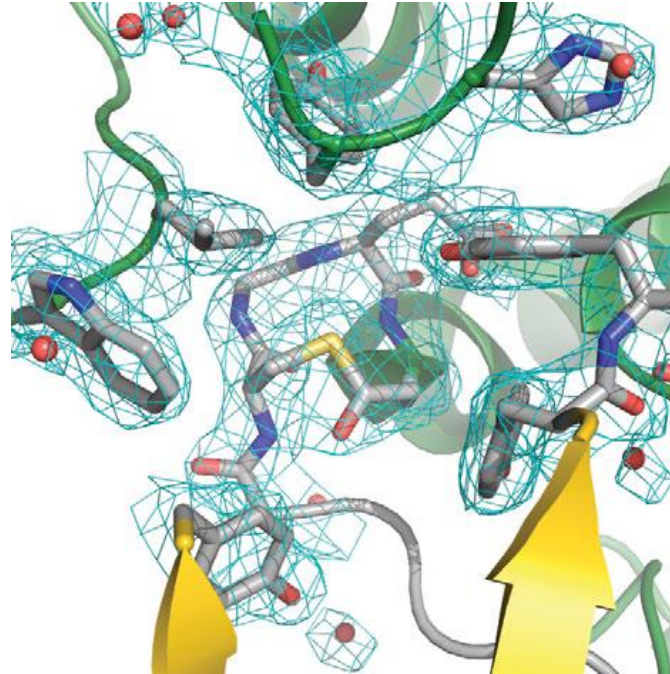
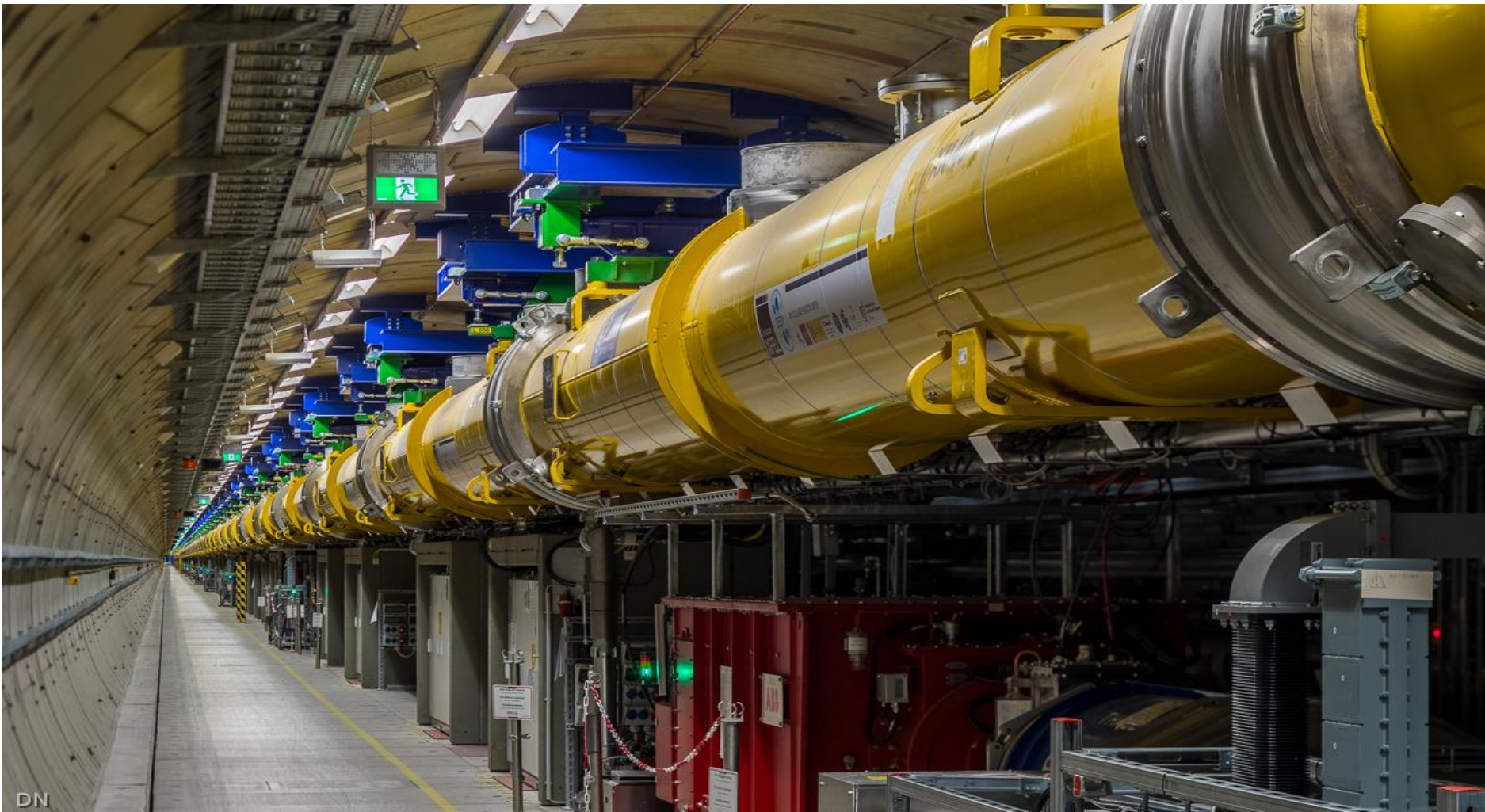

mosquito
immune system

HIV glycoprotein

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**
 - **Sucessfully started operation in 2017**

Accelerators for Neutron Science

- 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.
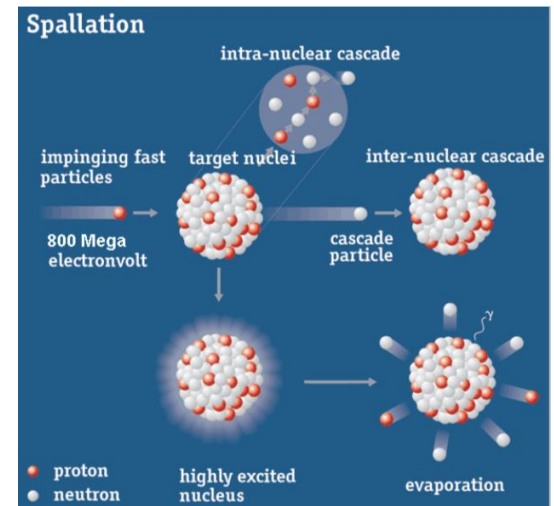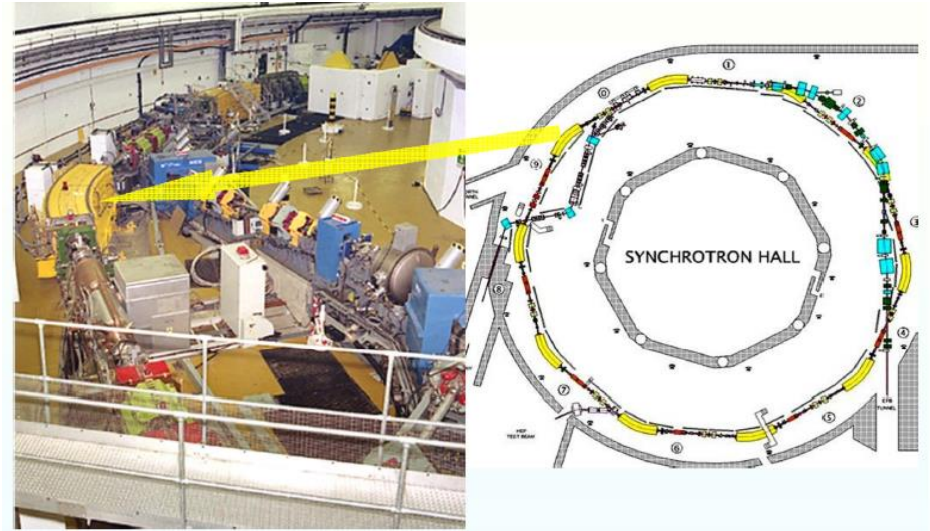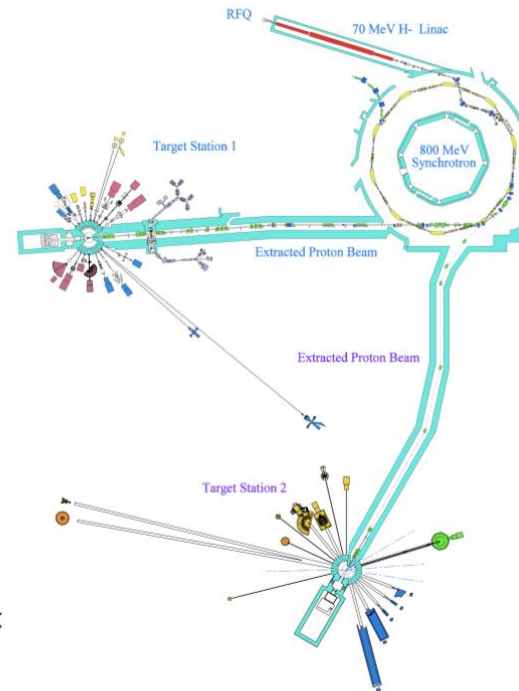
ISIS Accelerators and Targets
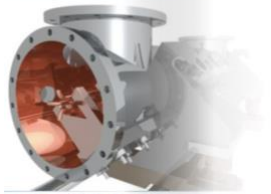
ISIS Accelerators and Targets

- 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).

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

29

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
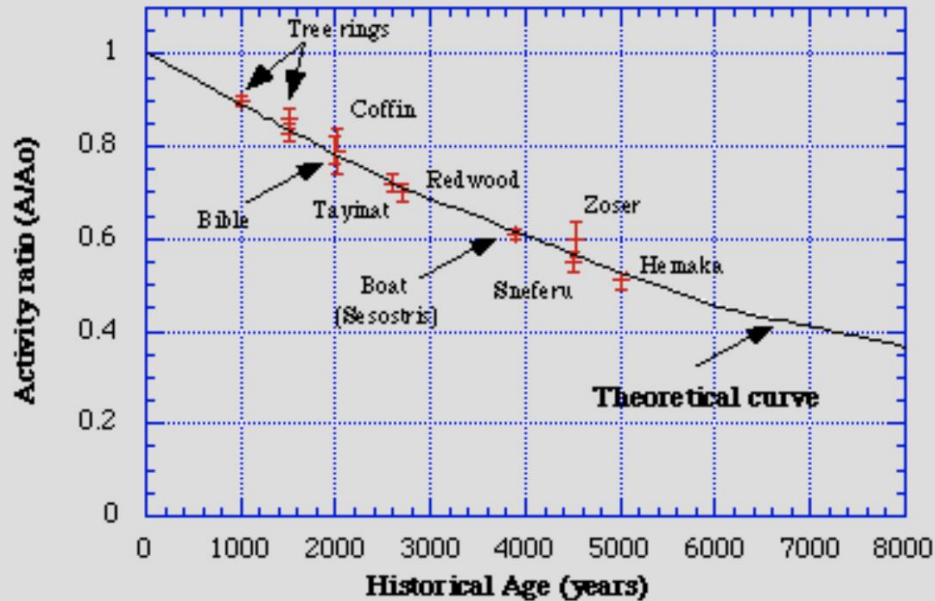
Ion Beam Implantation Products
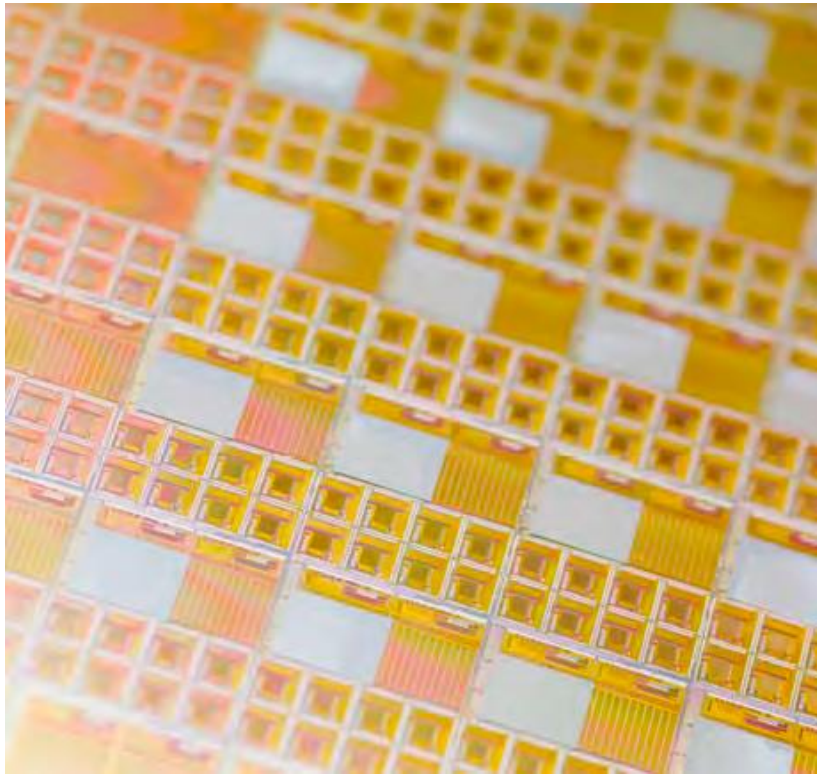
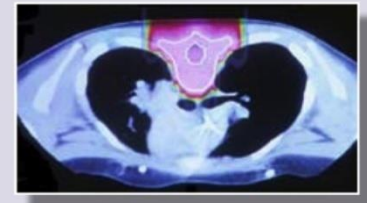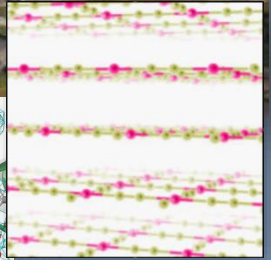# Accelerators for History & Culture Applications

Accelerator Mass Spectrometer

Radiocarbon Dating
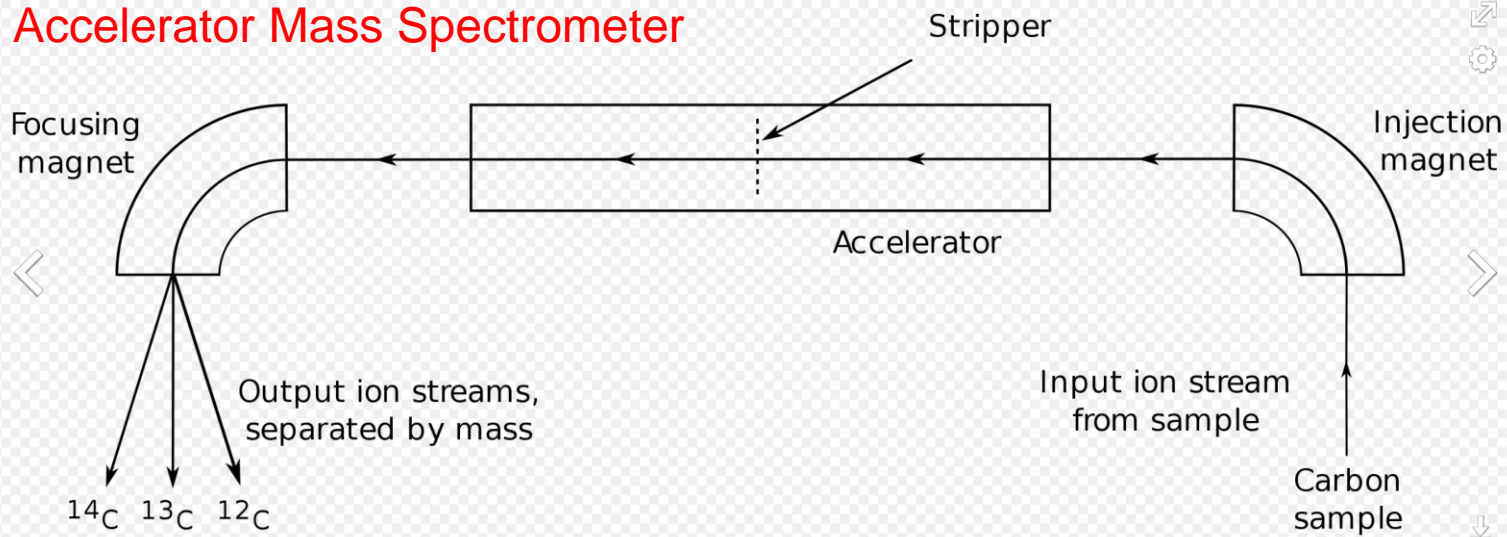
Niels Bohr

Louis Pasteur

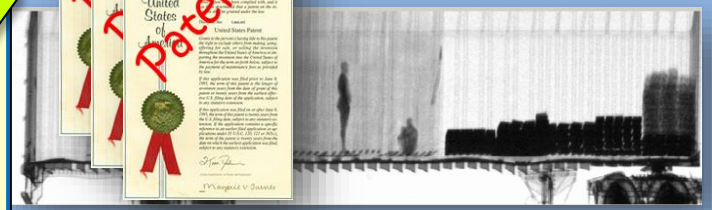Thomas Edison

PHYSICAL REVIEW LETTERS

PHYSICAL REVIEW LETTERS

Patent

PASTEUR'S QUADRANT

Basic Science and Technological Innovation
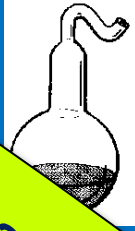
Donald E. Stokes

Accelerator Science and Technologies

Fundamental knowledge

Consideration of use

Protons / Ions

Bibliography