Lecture 3
Applications of Accelerators

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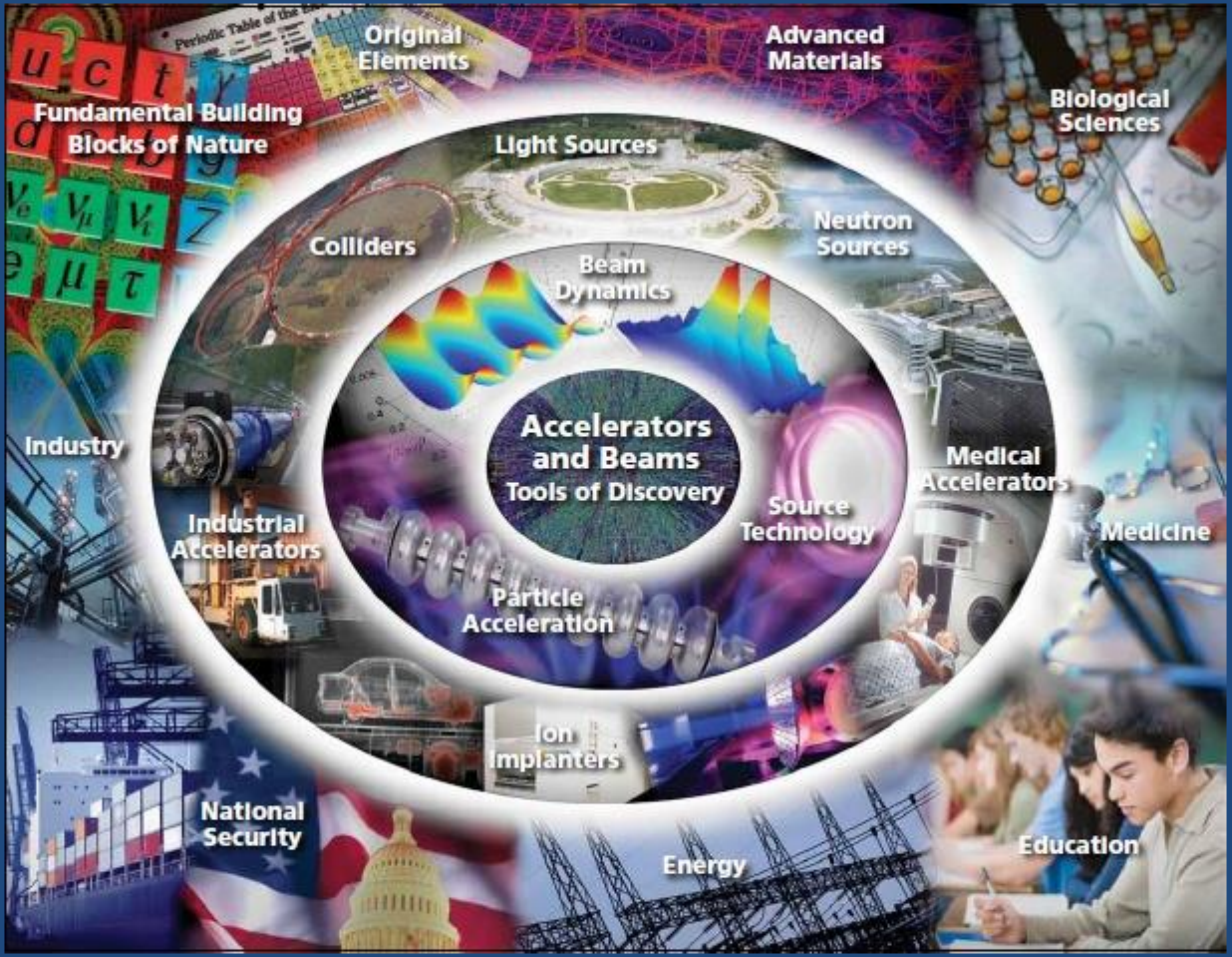
Introduction



24 Nobel Prizes in Physics with contribution from Accelerators… plus one!

Fraction of Nobel Prizes in Physics directly connected to accelerators is ~30%

Year	Name	Accelerator-Science Contribution to Nobel Prize-Winning Research
1939	Ernest O. Lawrence	Lawrence invented the cyclotron at the University of Californian at Berkeley in 1929 [12].
1951	John D. Cockcroft and Ernest T.S. Walton	Cockcroft and Walton invented their eponymous linear positive-ion accelerator at the Cavendish Laboratory in Cambridge, England, in 1932 [13].
1952	Felix Bloch	Bloch used a cyclotron at the Crocker Radiation Laboratory at the University of California at Berkeley in his discovery of the magnetic moment of the neutron in 1940 [14].
1957	Tsung-Dao Lee and Chen Ning Yang	Lee and Yang analyzed data on K mesons (θ and τ) from Bevatron experiments at the Lawrence Radiation Laboratory in 1955 [15], which supported their idea in 1956 that parity is not conserved in weak interactions [16].
1959	Emilio G. Segrè and Owen Chamberlain	Segrè and Chamberlain discovered the antiproton in 1955 using the Bevatron at the Lawrence Radiation Laboratory [17].
1960	Donald A. Glaser	Glaser tested his first experimental six-inch bubble chamber in 1955 with high-energy protons produced by the Brookhaven Cosmotron [18].
1961	Robert Hofstadter	Hofstadter carried out electron-scattering experiments on carbon-12 and oxygen-16 in 1959 using the SLAC linac and thereby made discoveries on the structure of nucleons [19].
1963	Maria Goeppert Mayer	Goeppert Mayer analyzed experiments using neutron beams produced by the University of Chicago cyclotron in 1947 to measure the nuclear binding energies of krypton and xenon [20], which led to her discoveries on high magic numbers in 1948 [21].
1967	Hans A. Bethe	Bethe analyzed nuclear reactions involving accelerated protons and other nuclei whereby he discovered in 1939 how energy is produced in stars [22].
1968	Luis W. Alvarez	Alvarez discovered a large number of resonance states using his fifteen-inch hydrogen bubble chamber and high-energy proton beams from the Bevatron at the Lawrence Radiation Laboratory [23].
1976	Burton Richter and Samuel C.C. Ting	Richter discovered the J/Ψ particle in 1974 using the SPEAR collider at Stanford [24], and Ting discovered the J/Ψ particle independently in 1974 using the Brookhaven Alternating Gradient Synchrotron [25].
1979	Sheldon L. Glashow, Abdus Salam, and Steven Weinberg	Glashow, Salam, and Weinberg cited experiments on the bombardment of nuclei with neutrinos at CERN in 1973 [26] as confirmation of their prediction of weak neutral currents [27].
1980	James W. Cronin and Val L. Fitch	Cronin and Fitch concluded in 1964 that CP (charge-parity) symmetry is violated in the decay of neutral K mesons based upon their experiments using the Brookhaven Alternating Gradient Synchrotron [28].
1981	Kai M. Siegbahn	Siegbahn invented a weak-focusing principle for betatrons in 1944 with which he made significant improvements in high-resolution electron spectroscopy [29].
1983	William A. Fowler	Fowler collaborated on and analyzed accelerator-based experiments in 1958 [30], which he used to support his hypothesis on stellar-fusion processes in 1957 [31].
1984	Carlo Rubbia and Simon van der Meer	Rubbia led a team of physicists who observed the intermediate vector bosons W and Z in 1983 using CERN's proton-antiproton collider [32], and van der Meer developed much of the instrumentation needed for these experiments [33].
1986	Ernst Ruska	Ruska built the first electron microscope in 1933 based upon a magnetic optical system that provided large magnification [34].
1988	Leon M. Lederman, Melvin Schwartz, and Jack Steinberger	Lederman, Schwartz, and Steinberger discovered the muon neutrino in 1962 using Brookhaven's Alternating Gradient Synchrotron [35].
1989	Wolfgang Paul	Paul's idea in the early 1950s of building ion traps grew out of accelerator physics [36].
1990	Jerome I. Friedman, Henry W. Kendall, and Richard E. Taylor	Friedman, Kendall, and Taylor's experiments in 1974 on deep inelastic scattering of electrons on protons and bound neutrons used the SLAC linac [37].
1992	Georges Charpak	Charpak's development of multiwire proportional chambers in 1970 were made possible by accelerator-based testing at CERN [38].
1995	Martin L. Perl	Perl discovered the tau lepton in 1975 using Stanford's SPEAR collider [39].
2004	David J. Gross, Frank Wilczek, and H. David Politzer	Gross, Wilczek, and Politzer discovered asymptotic freedom in the theory of strong interactions in 1973 based upon results from the SLAC linac on electron-proton scattering [40].
2008	Makoto Kobayashi and Toshihide Maskawa	Kobayashi and Maskawa's theory of quark mixing in 1973 was confirmed by results from the KEKB accelerator at KEK (High Energy Accelerator Research Organization) in Tsukuba, Ibaraki Prefecture, Japan, and the PEP II (Positron Electron Project II) at SLAC [41], which showed that quark mixing in the six-quark model is the dominant source of broken symmetry [42].

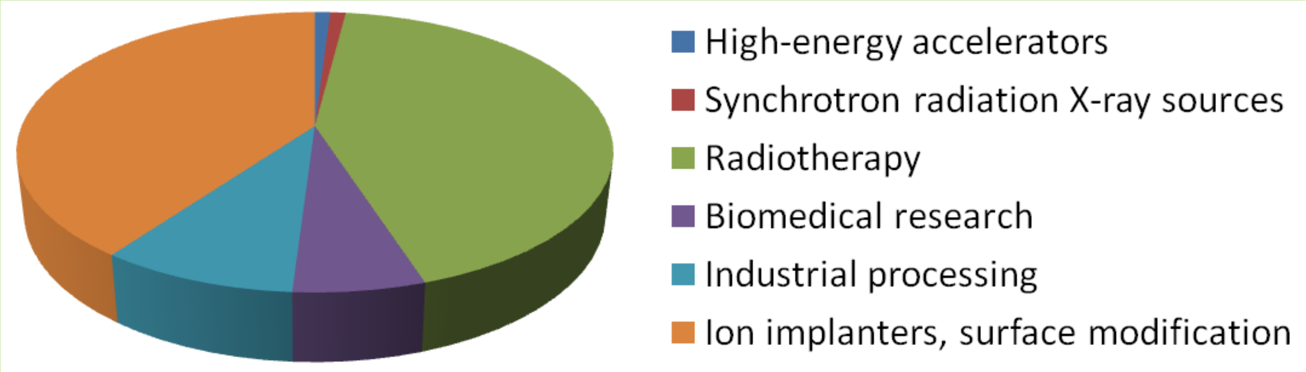
A.Chao and E. Haussecker "*Impact of Accelerator Science on Physics Research*", published in ICFA Newsletter, Dec 2010; & submitted to the Physics in Perspective Journal, Dec 2010.

Nobel Prize in Physics 2013

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider".*

Accelerators Worldwide

The number of accelerators worldwide exceed 20000



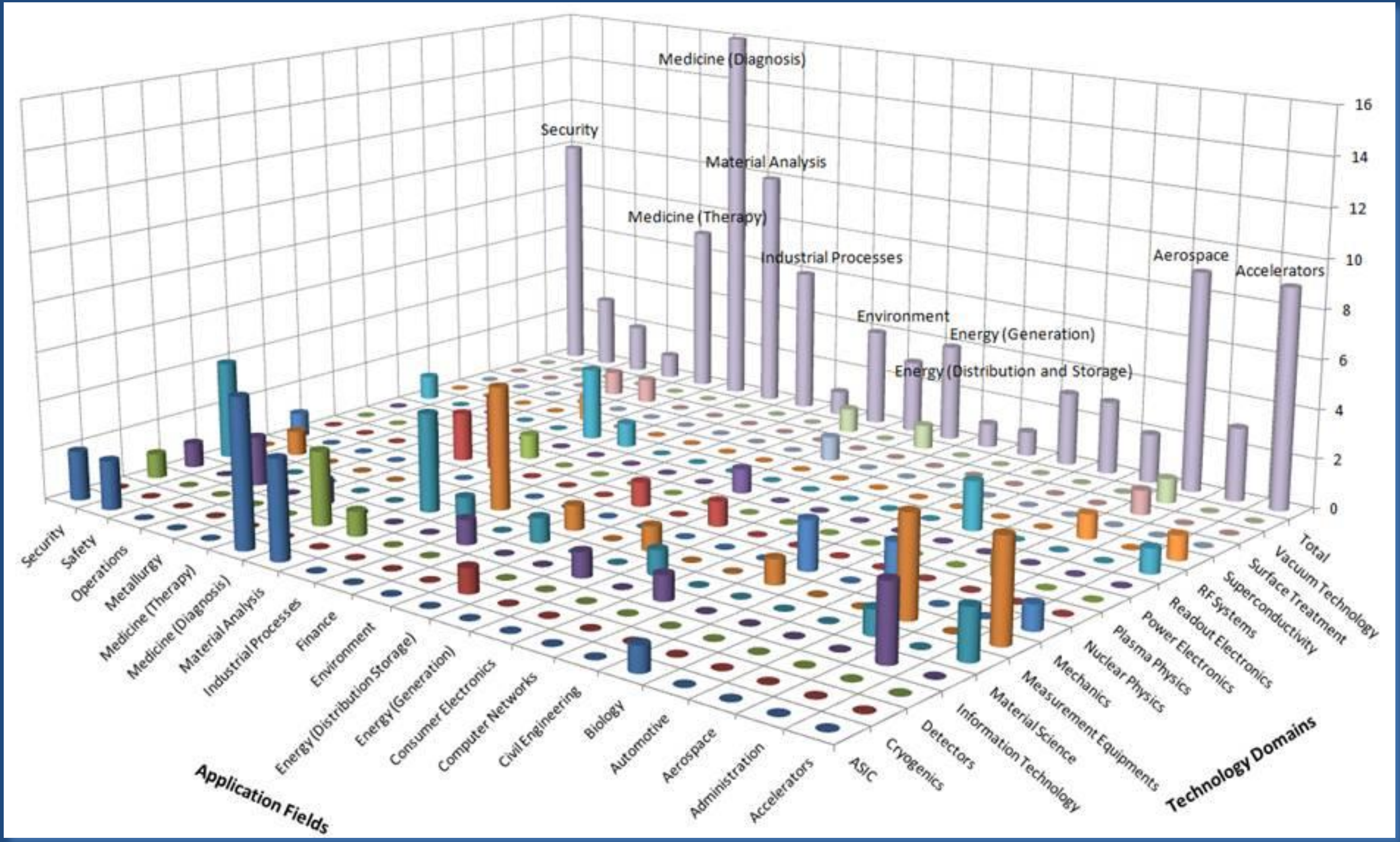
- Market for **medical and industrial** accelerators exceeds **$3.5 billion**. All products that are processed, treated, or inspected by particle beams have a collective annual value of more than $500 billion [1]

[1] http://www.acceleratorsamerica.org/

Accelerators are not only for high-energy physics

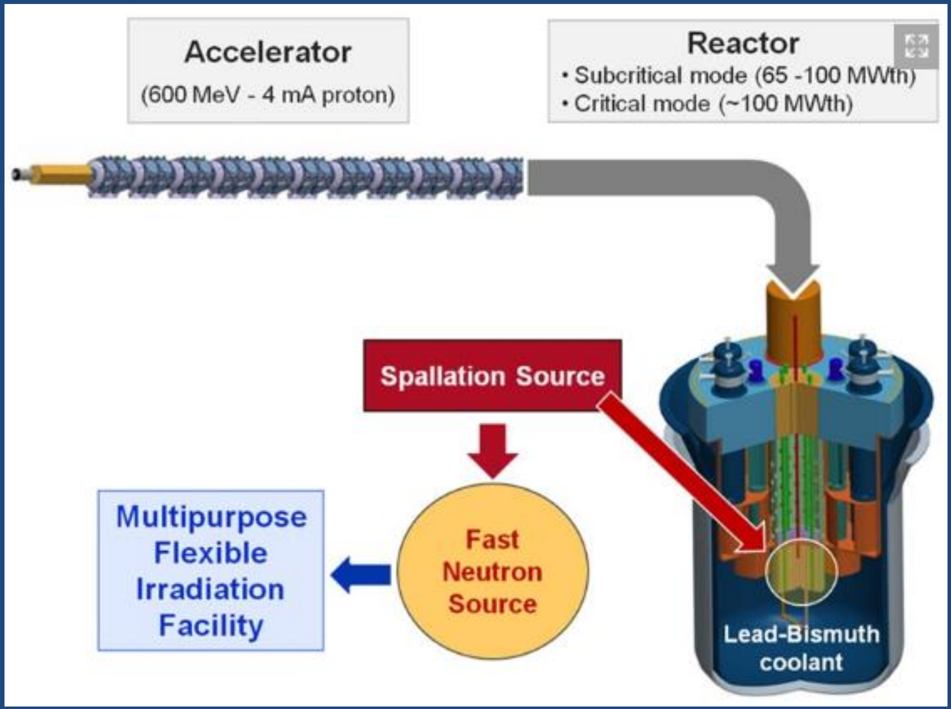
Application of Technologies

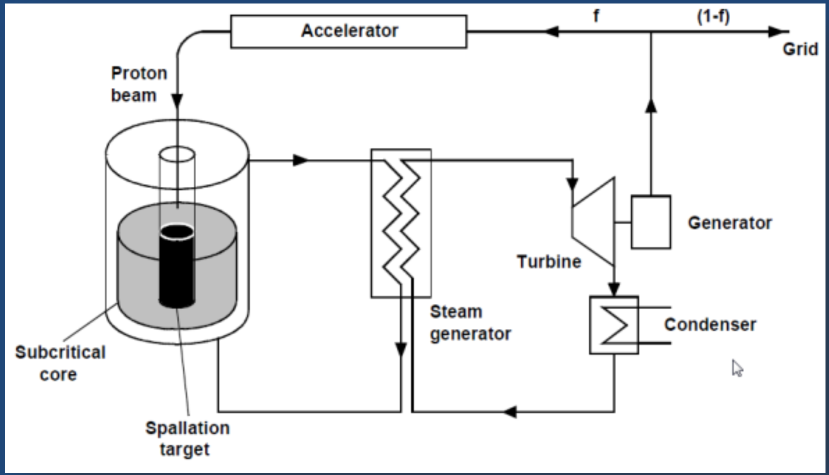
Frontier research infrastructure plays key role in a society of scientific and technological knowledge and know-how.



Accelerators for Energy

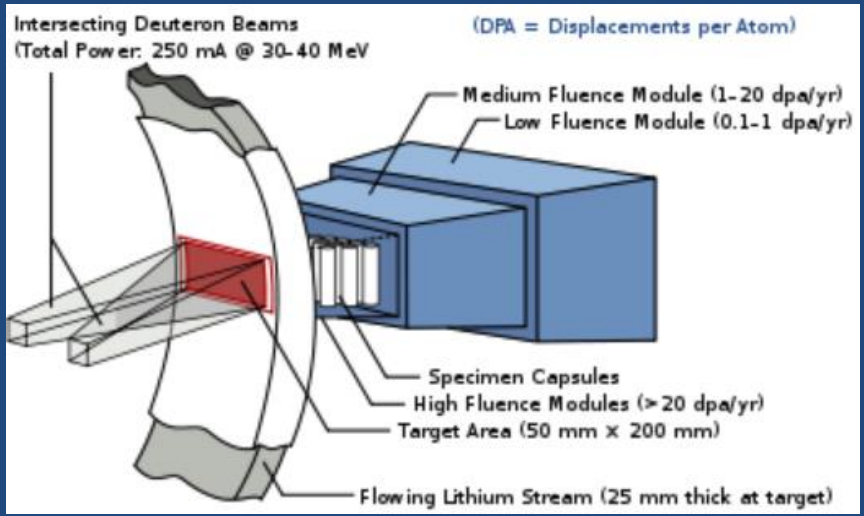
Accelerators can drive next-generation reactors (ADSR) that burn non-fissile fuel, such as thorium





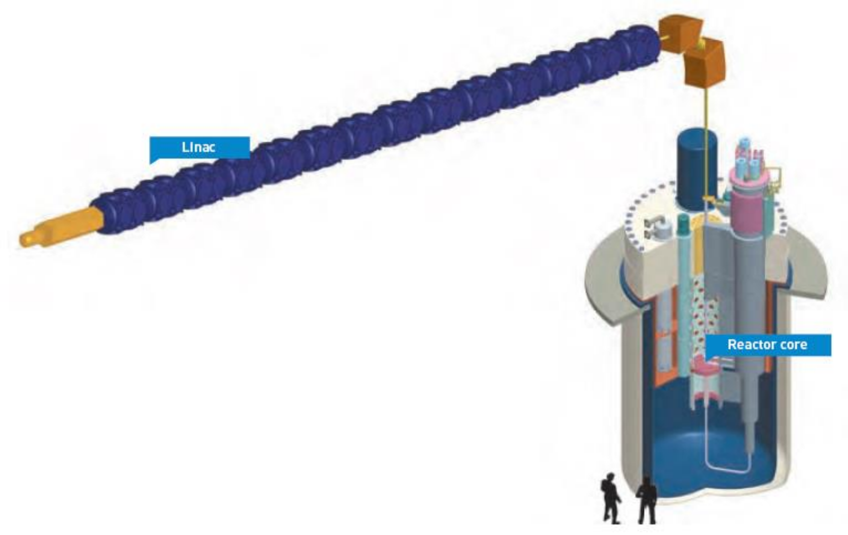
MYRRHA: Multi-purpose hybrid research reactor for high-tech applications, conceived as an accelerator driven system

International Fusion Material Irradiation Facility (IFMIF)



Accelerators for Energy

- Accelerator-Driven Subcritical System (ADS)
  - 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.



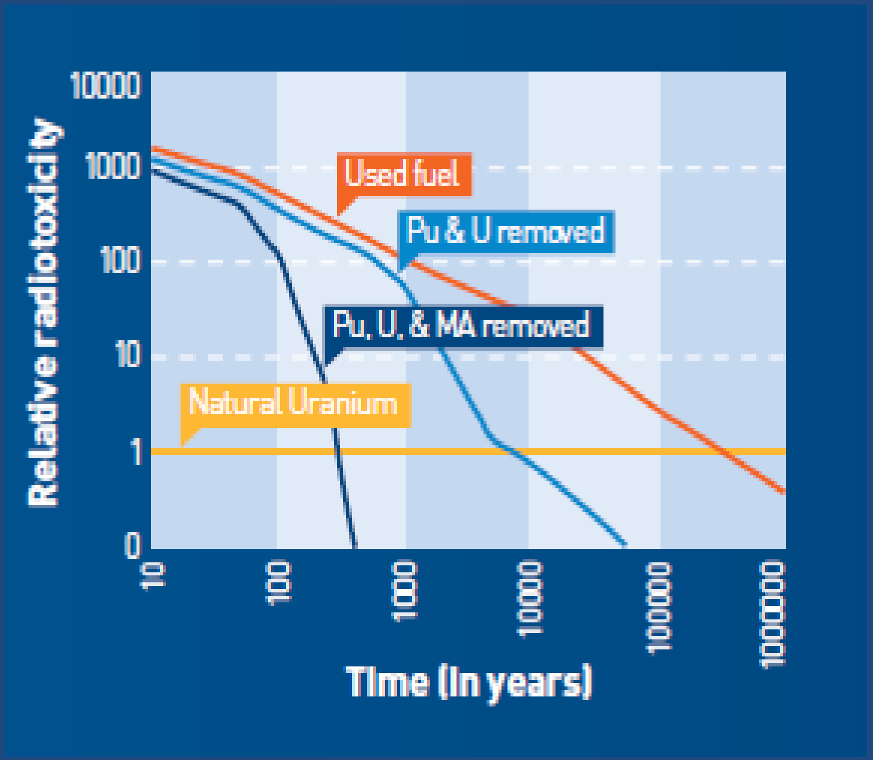
Use of Th instead of U produces less actinides.

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

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

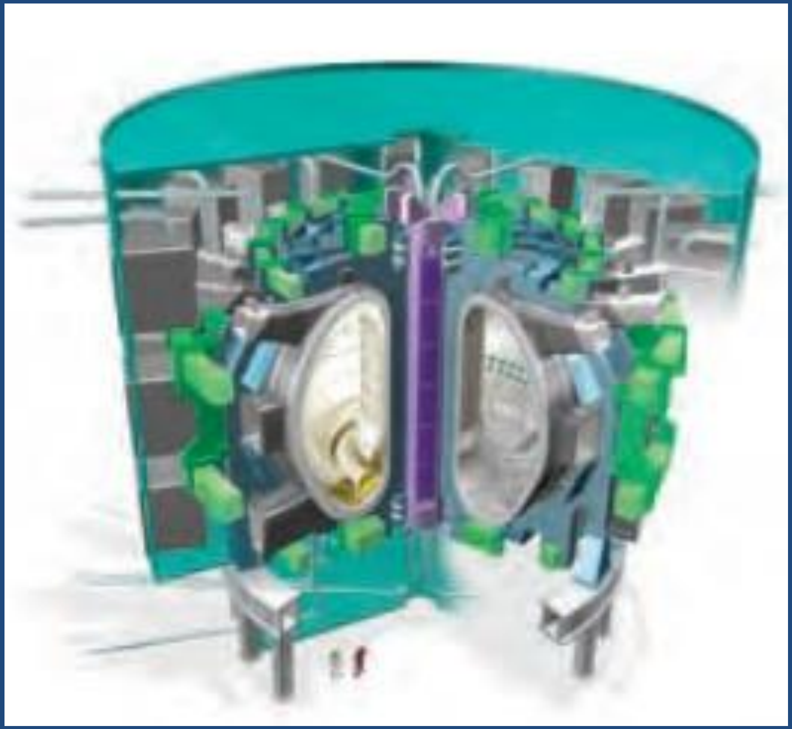
Accelerators for Energy

- ADS & Radioactive Waste Transmutation
  - ADS 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.

Innovation Education CERN uniting people Research

CERN: Particle Physics & Innovation

- Interfacing between fundamental science and key technological developments

- CERN Technologies and Innovation

Accelerating particle beams

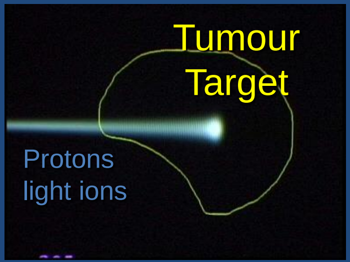
Detecting particles

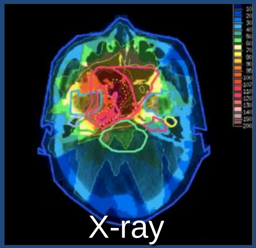
Large-scale computing (Grid)

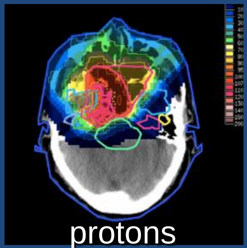
Medical Application - Example of Particle Physics Spin-off

Combining Physics, ICT, Biology and Medicine to fight cancer

Hadron Therapy



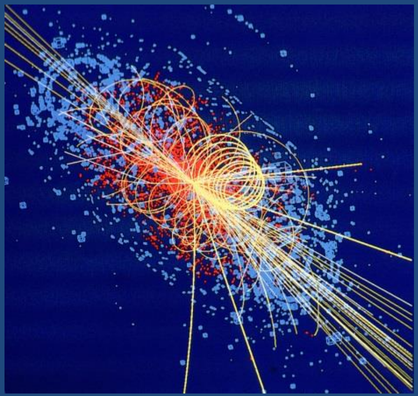




Leadership in Ion Beam Therapy now in Europe and Japan

Accelerating particle beams
~30’000 accelerators worldwide
~17’000 used for medicine

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

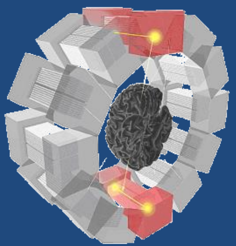


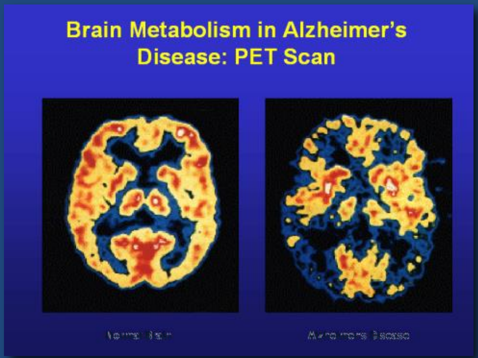
Detecting particles

Imaging

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

PET Scanner





Accelerators for Medical Use

- **Production of radionuclides with (low-energy) cyclotrons**
  - **Imaging**
  - Therapy
- **Electron linacs for conventional radiation therapy.**
- **Medium-energy cyclotrons and synchrotrons for hadron therapy with protons (250 MeV) or light ion beams (400 MeV/u 12C-ions).**

Accelerators for Medicine

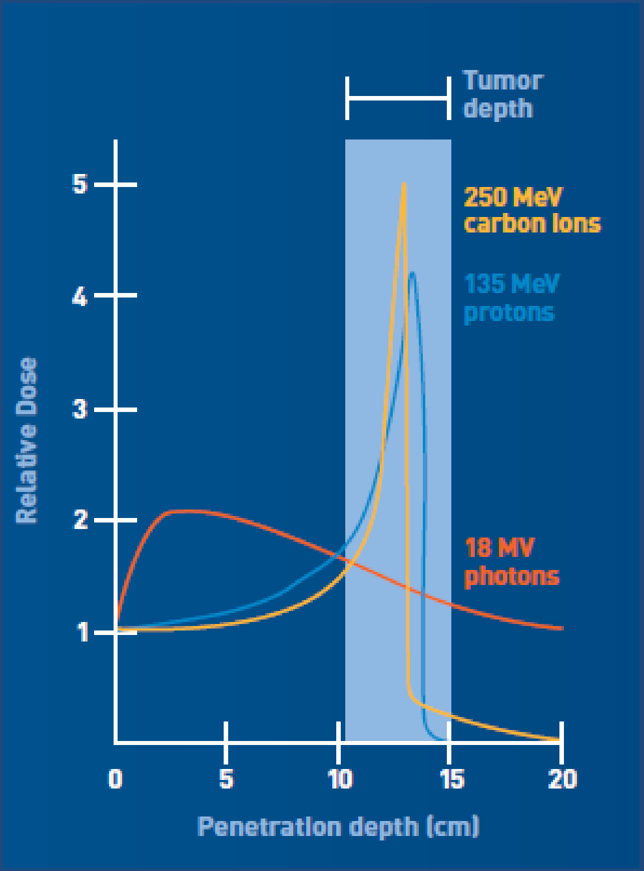
- Medical Therapy
  - X-rays have been used for decades to destroy tumours.
  - For deep-seated tumours and/or minimizing dose in surrounding healthy tissue use hadrons (protons, light ions).
  - Accelerator-based hadrontherapy facilities.

Accelerator cancer therapy

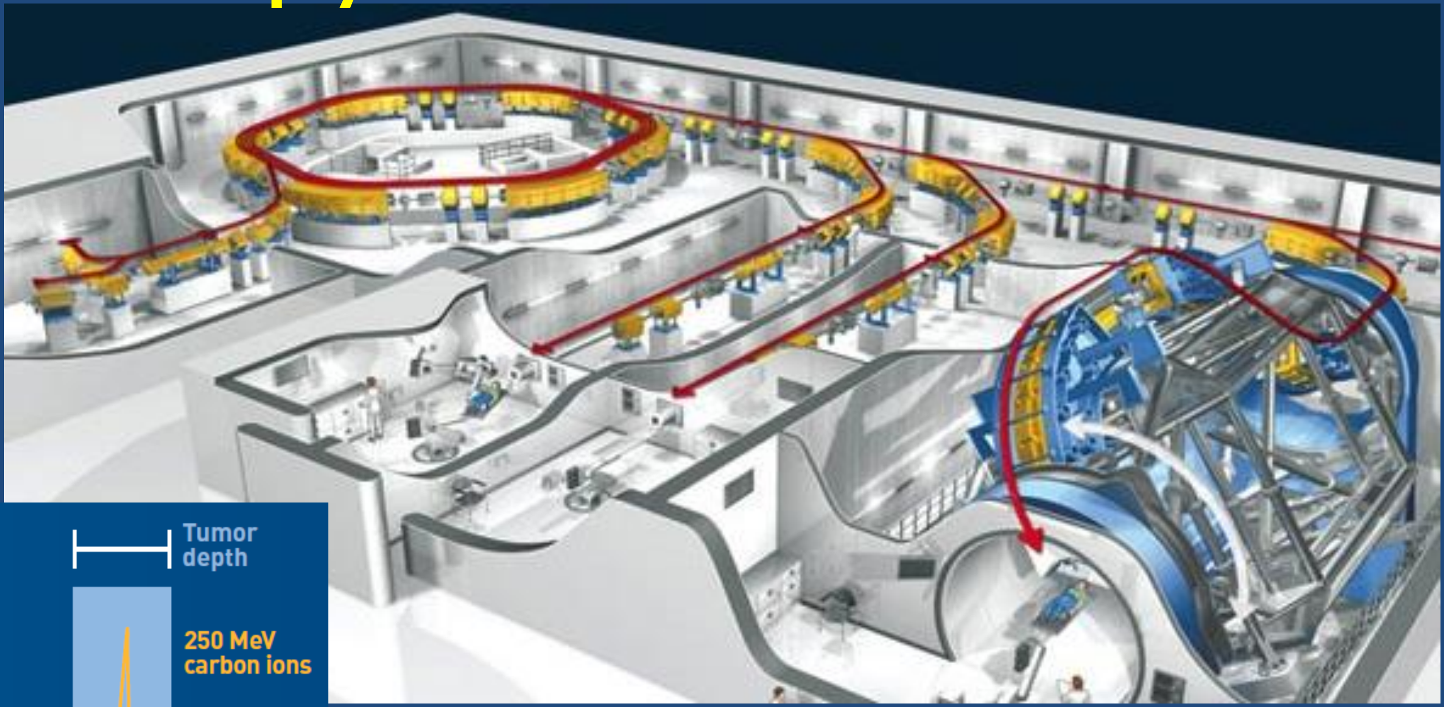
Loma Linda Proton Treatment Centre Constructed at FNAL

Accelerators for Medicine

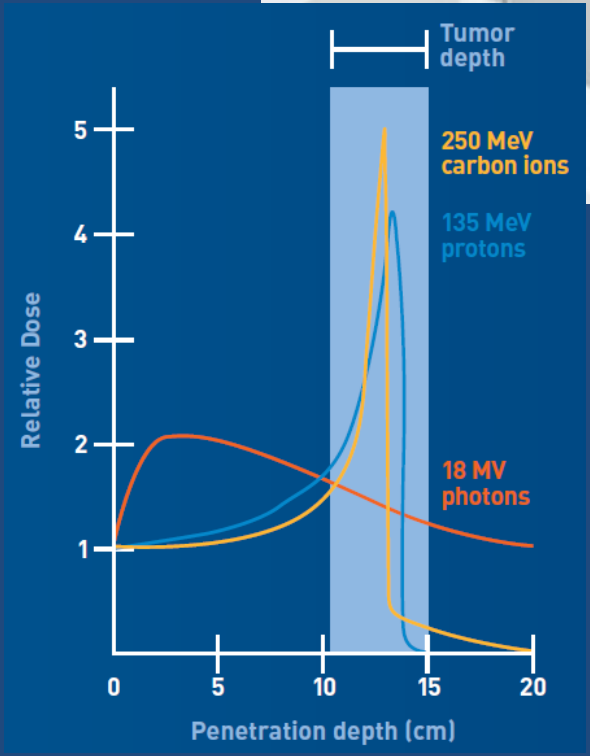
Photons, Protons and Light Ions

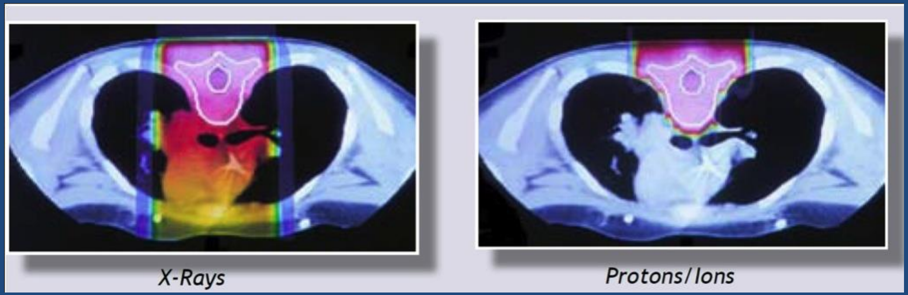


Radiotherapy with Ions



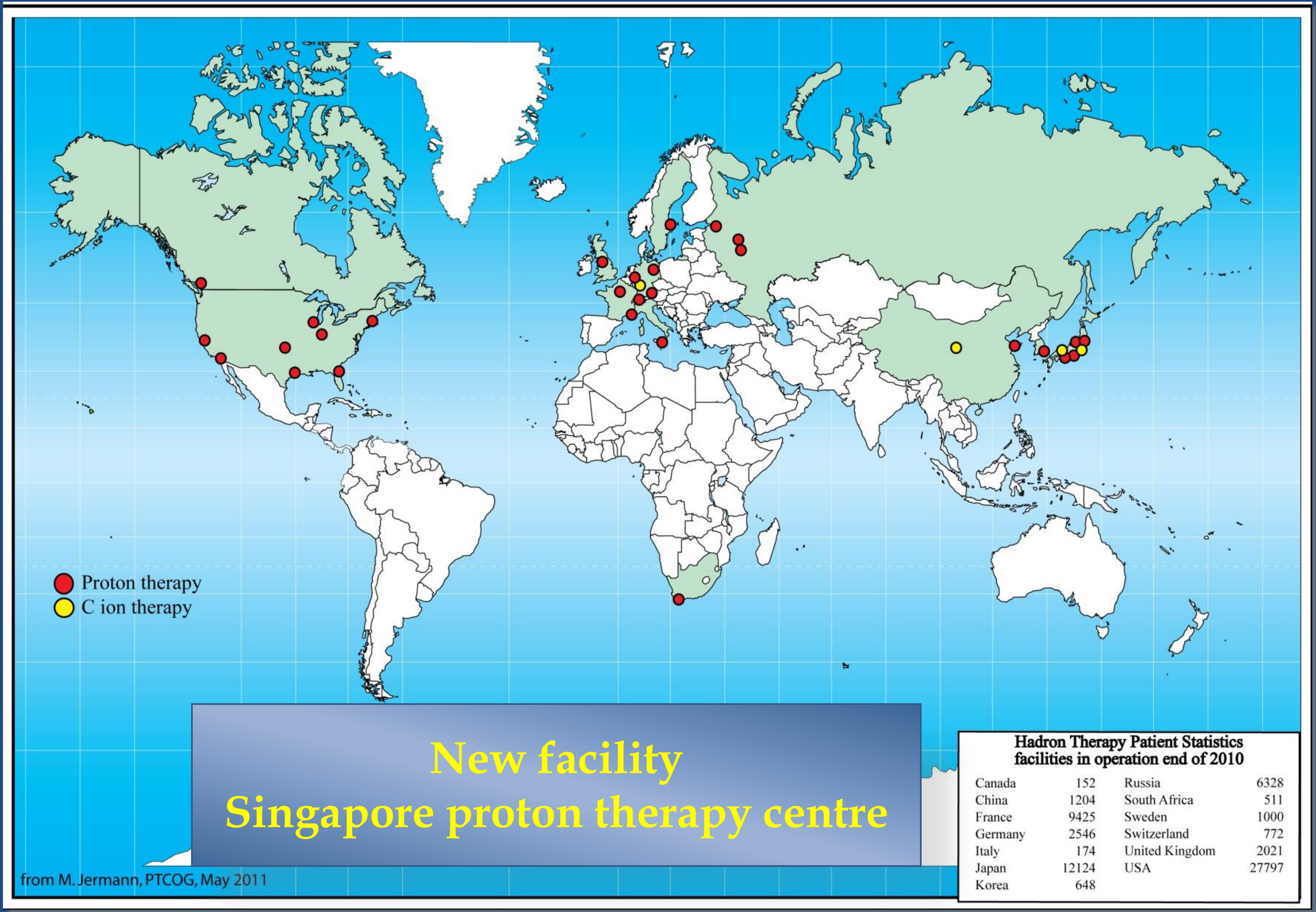
Heidelberg Ion Therapy Facility (protons & carbon)





Cancer therapy with x-rays and protons or heavier ions

Centers for HADRON Therapy
in operation end of 2010



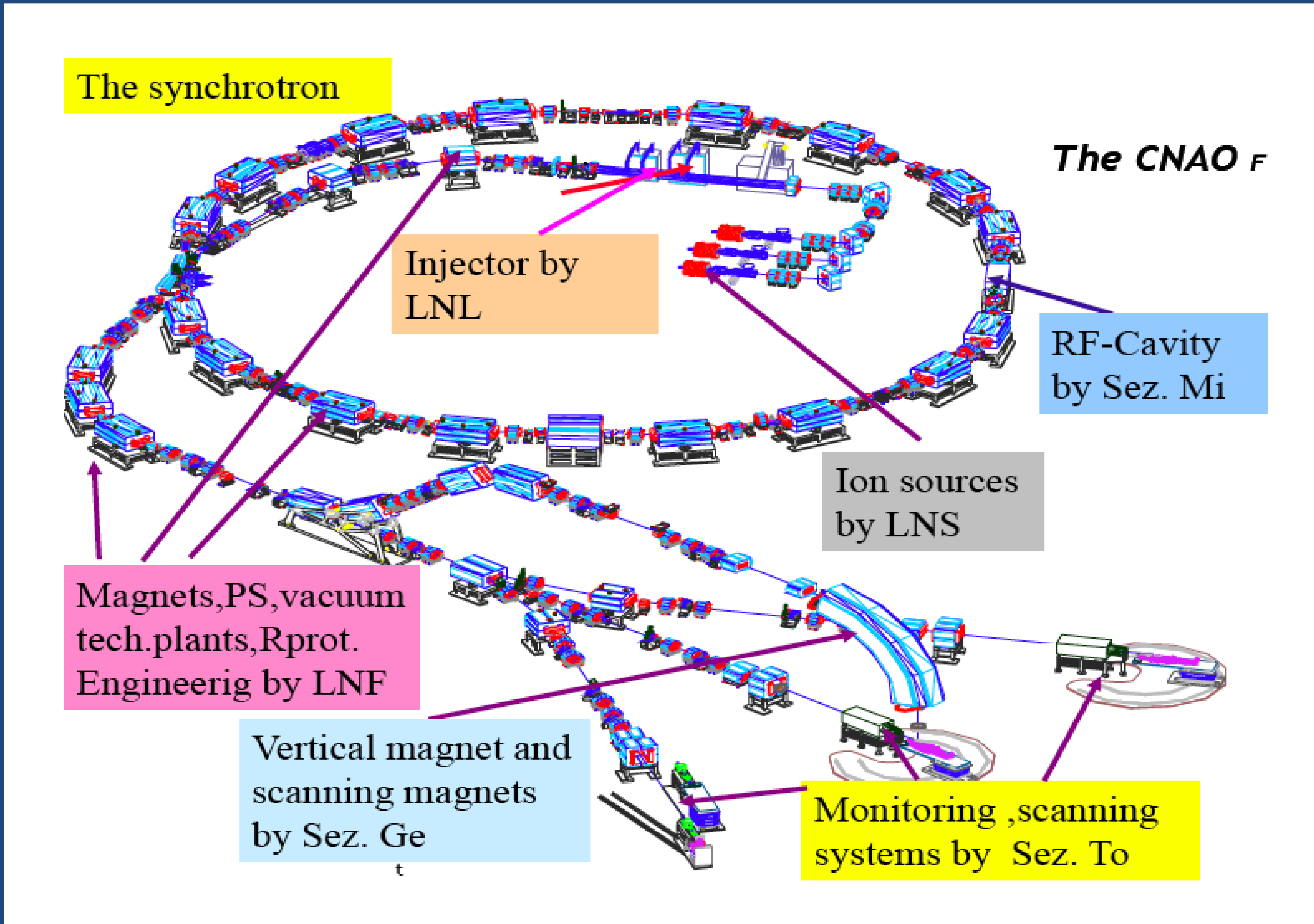
Hadron Therapy Patient Statistics facilities in operation end of 2010

Canada	152	Russia	6328
China	1204	South Africa	511
France	9425	Sweden	1000
Germany	2546	Switzerland	772
Italy	174	United Kingdom	2021
Japan	12124	USA	27797
Korea	648		

New facility
Singapore proton therapy centre

Worldwide: 30 centres (4 have C-ions): ~ 65’000 patients
Europe: 9 centres (with C-ions at GSI and Heidelberg): ~ 16’000 patients

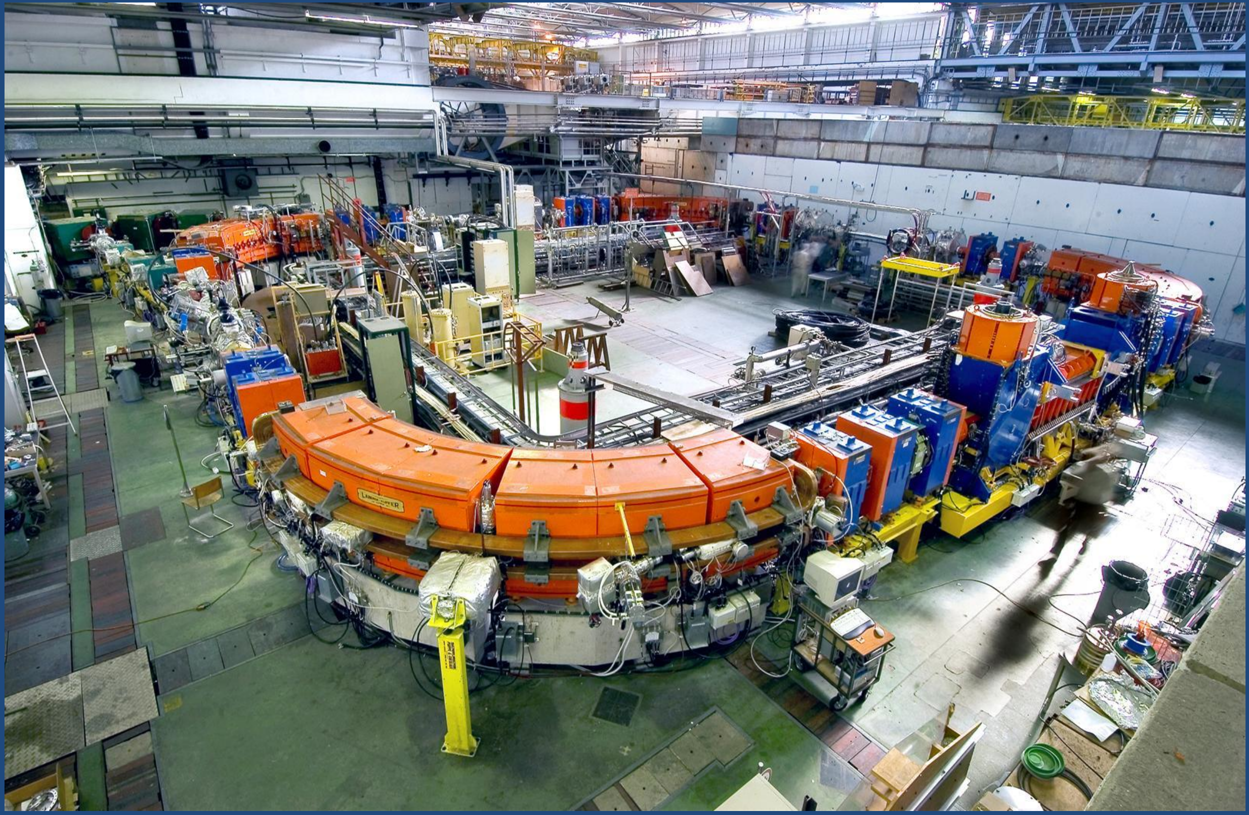
CNAO in Pavia (Italy)



Growing interest in hadron therapy

Interest/plans for new facilities in Europe - Bulgaria, Greece, Norway, Denmark, the Netherlands, UK, Spain

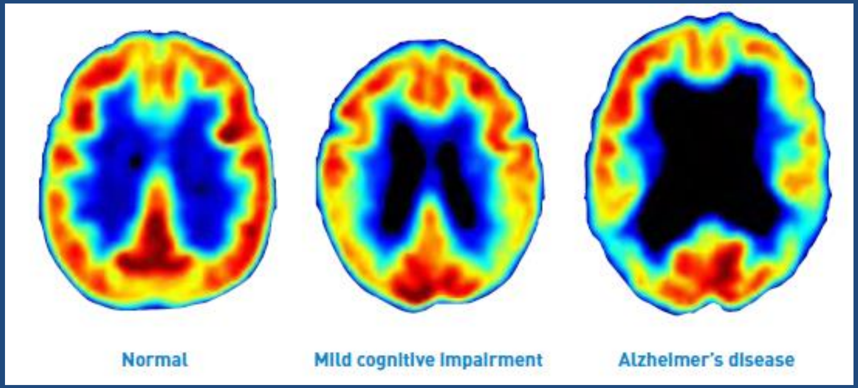
Need more research and biomedical studies with different ions **(BioLEIR)**



Accelerators for Medicine

- Medical Imaging
  - Radioisotopes have become vital components in medicine.
    - Produced at reactors or accelerators.
  - Positron Emission Tomography (PET)
    - Requires positron emitter ^{18}F
  - ^{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



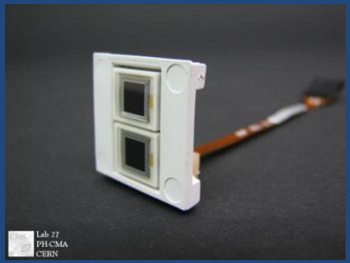
PET Scan

The Virtual Cycle

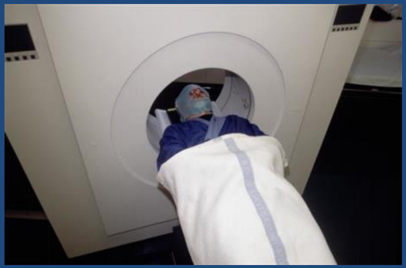
- The synergy between basic research and innovation does not only lead to societal and economic impact, but also, and very importantly, to the production of increased opportunities for further development.

- The cycle must remain strong, be continuous and be supported on the long term.

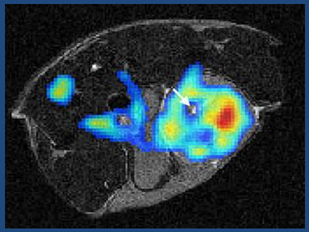
The Virtual Cycle
PET Scans (1970s-2010s)



Technology
(APDs...)



Technology
(scanner…)



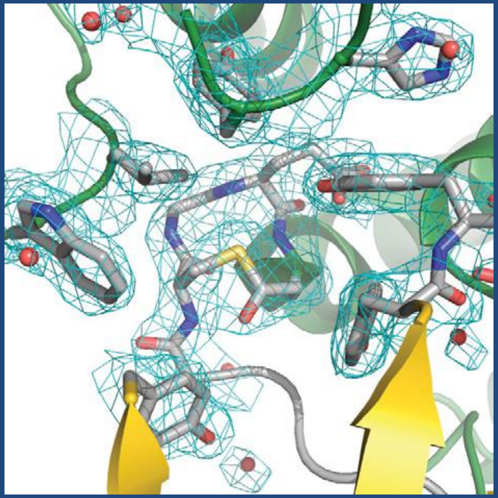
Today
PET/MRI

Tomorrow

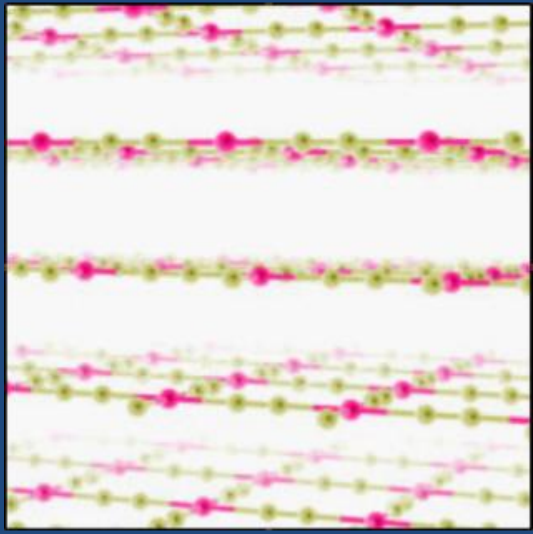
Technology
(crystals…)

Neutrons & X-rays

Protein structure revealed with help of light sources



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



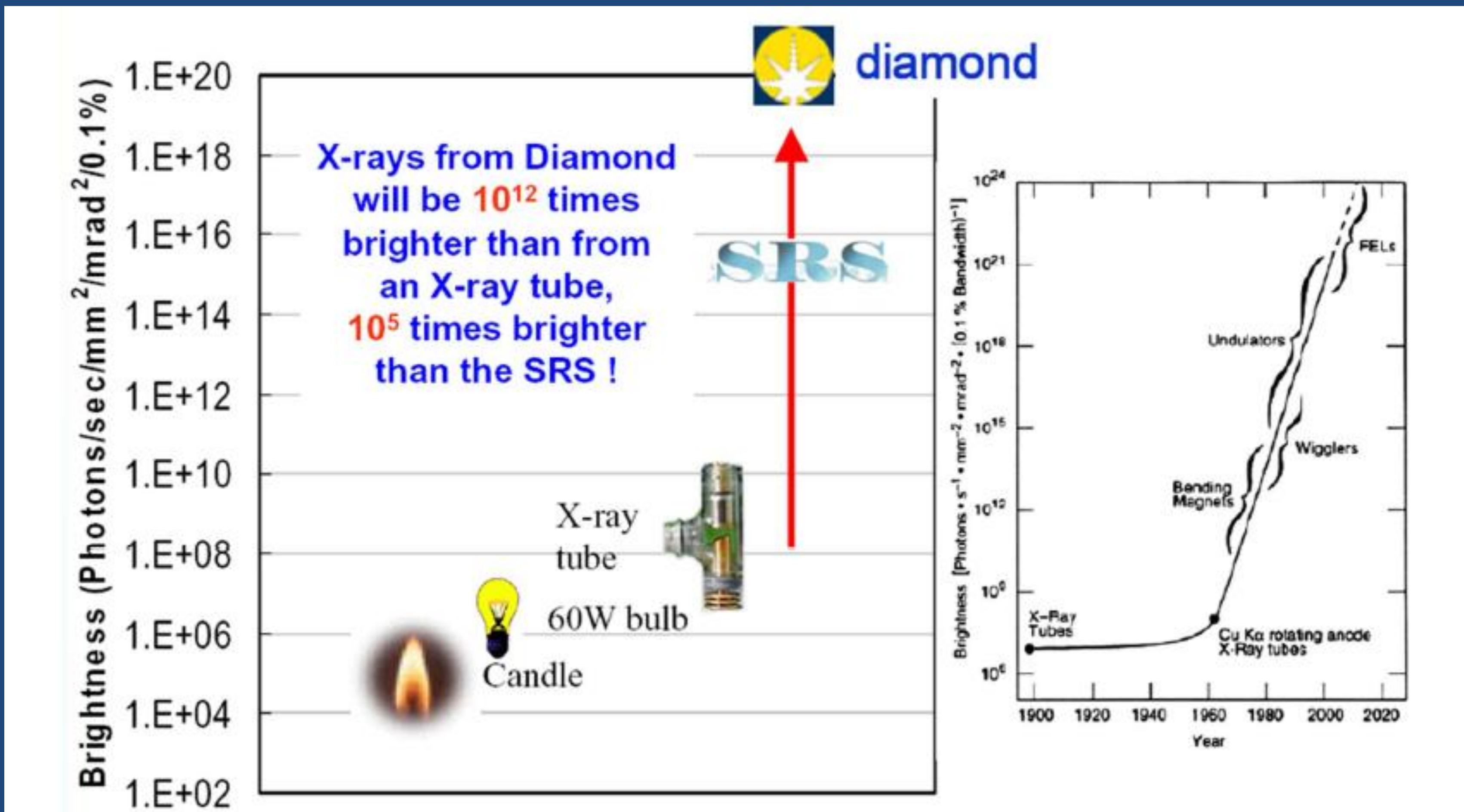
Neutron and X-ray imaging essential for studies of proteins and advanced materials.

diamond

Science & Technology Facilities Council

2-d material (graphene)

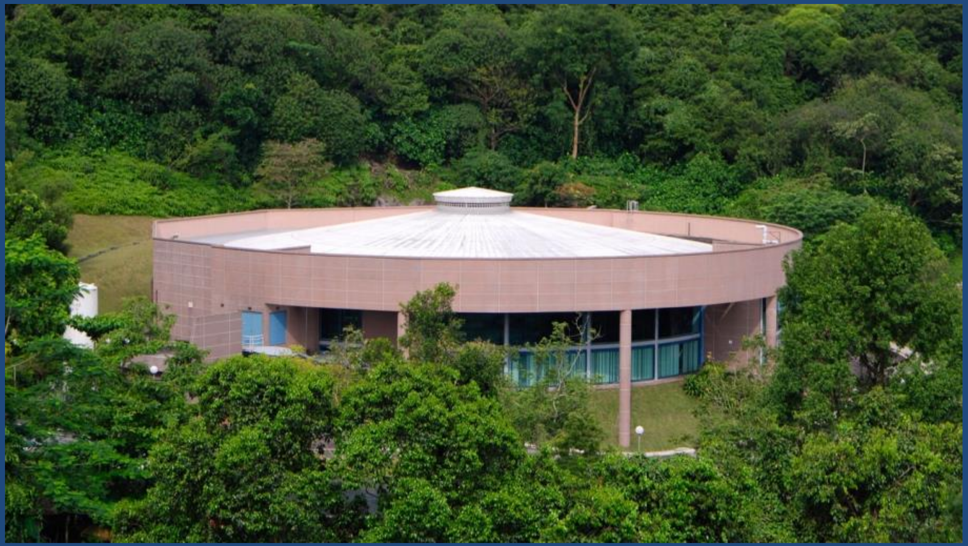
Accelerators for Synchrotron Light



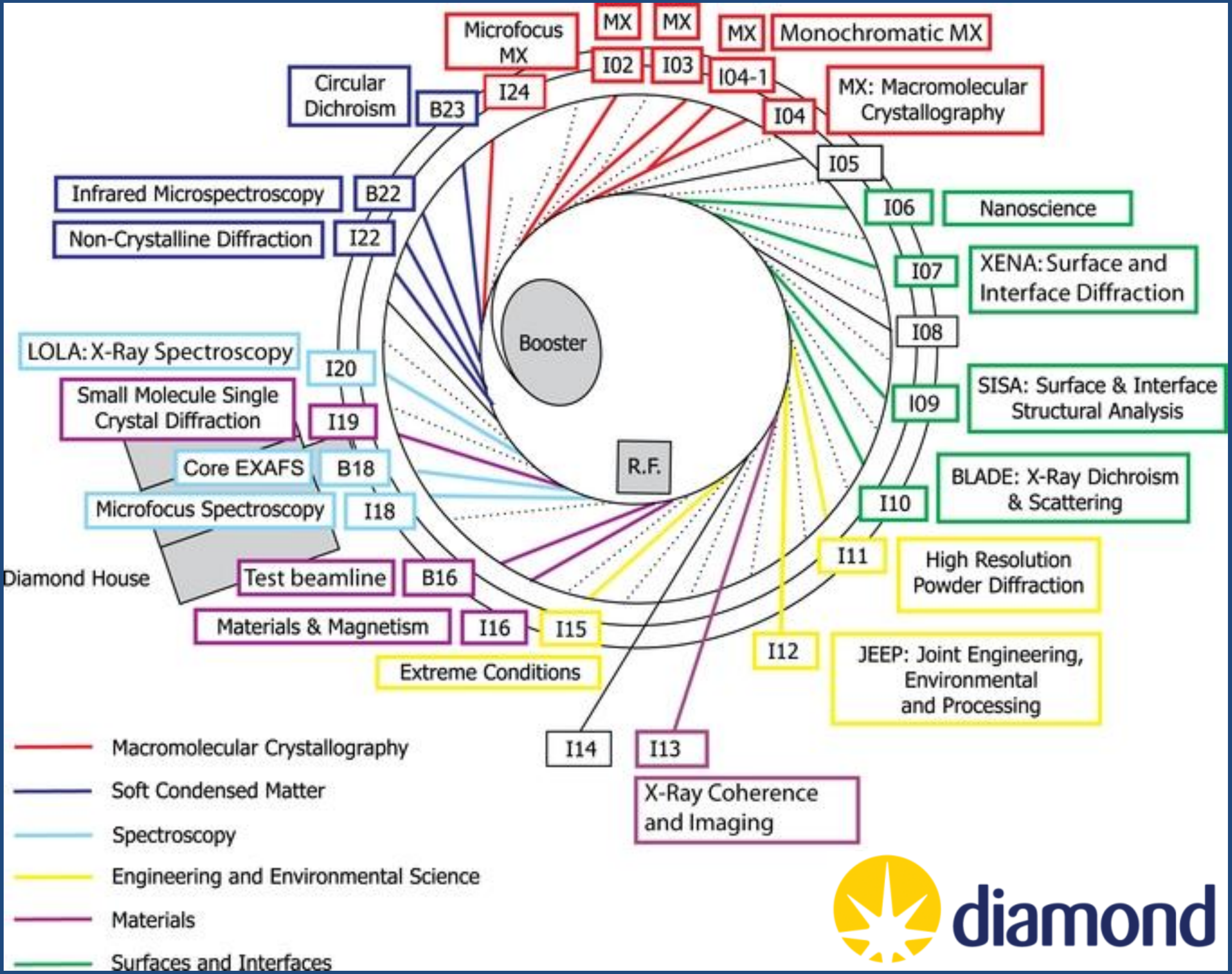
Synchrotron Source of X-rays

Diamond Light Source, Harwell
Science and Innovation Campus, UK

Singapore Synchrotron Light Source
National University of Singapore



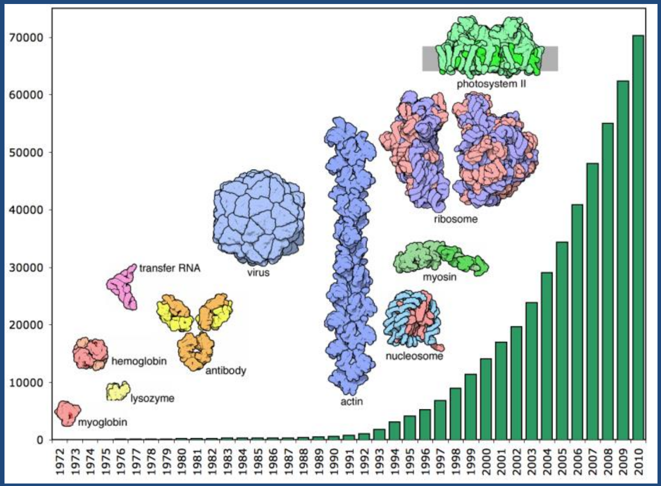
Diamond Beamlines



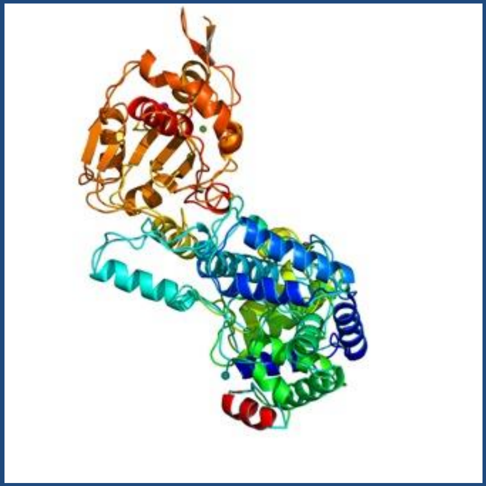
Accelerators for Synchrotron Light

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.



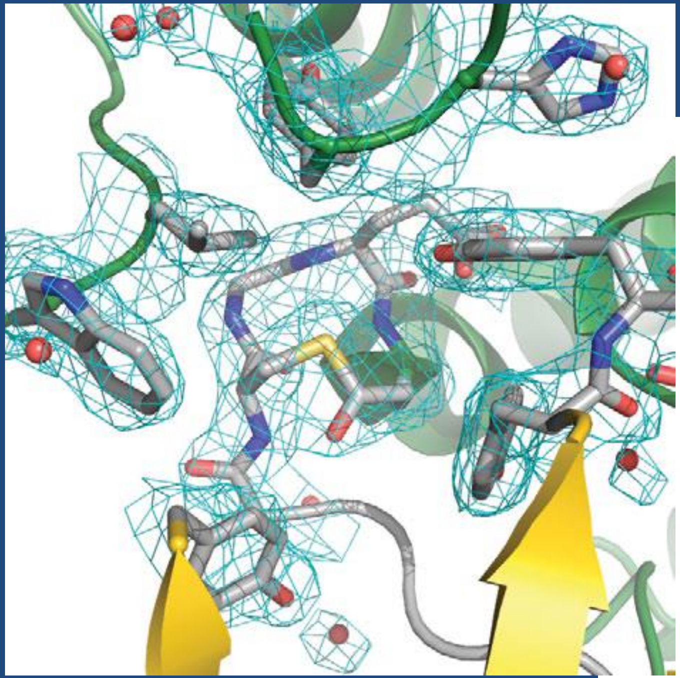
Protein Data Bank



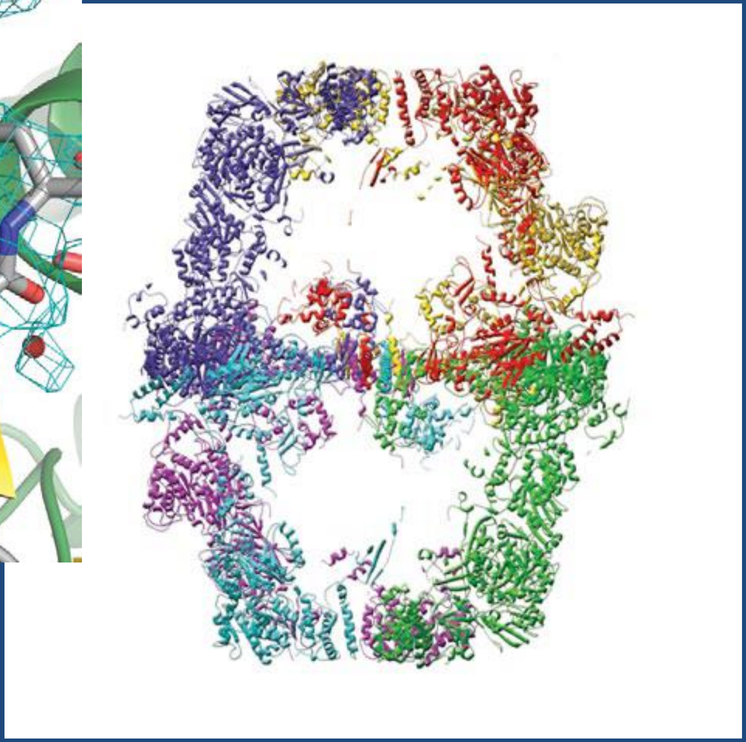
The trimer of the Lassa nucleoprotein, part of the Lassa virus

Protein Structure Revealed by Light Sources

HIV glycoprotein

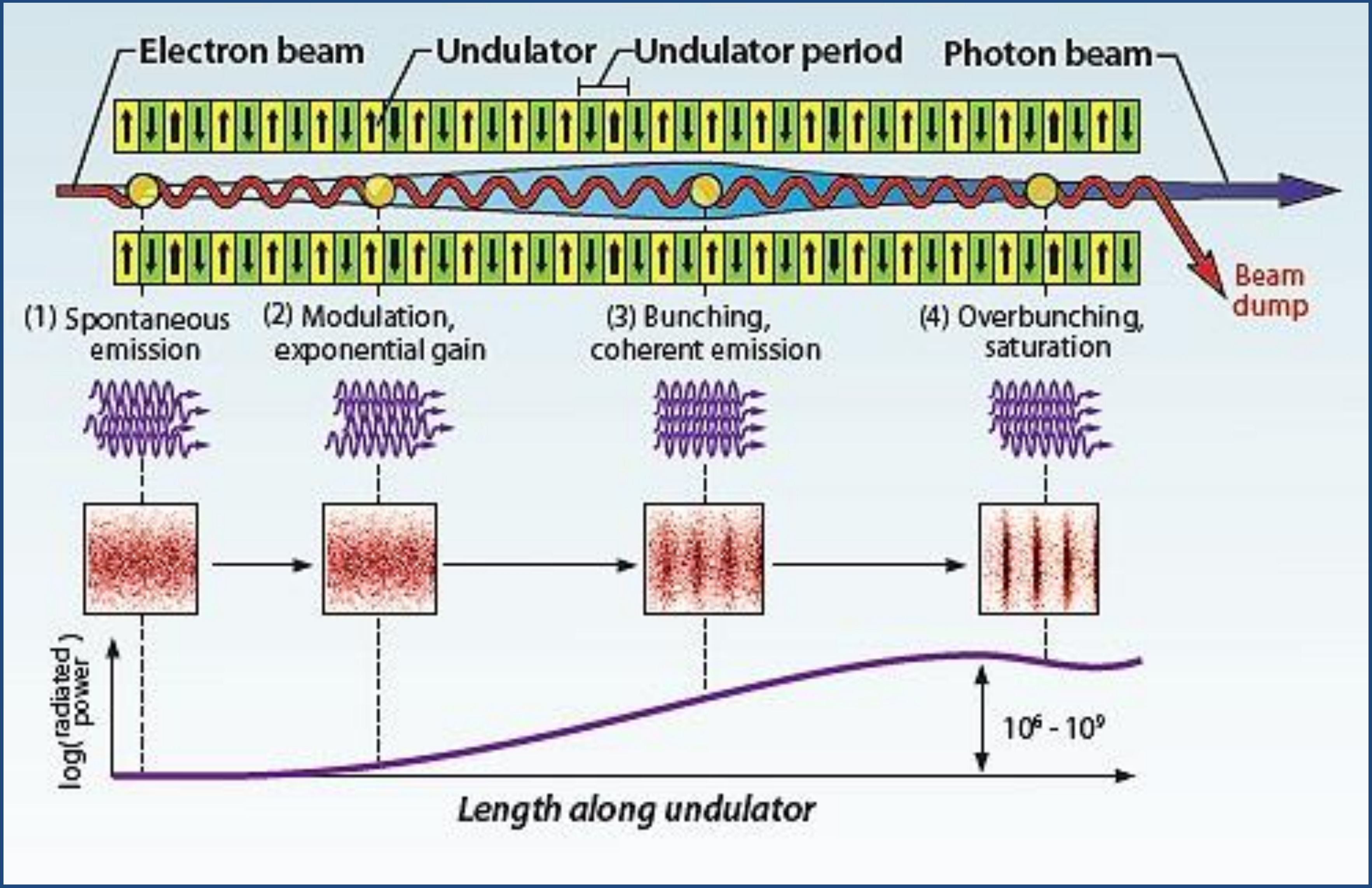


mosquito
immune system



yeast enzyme

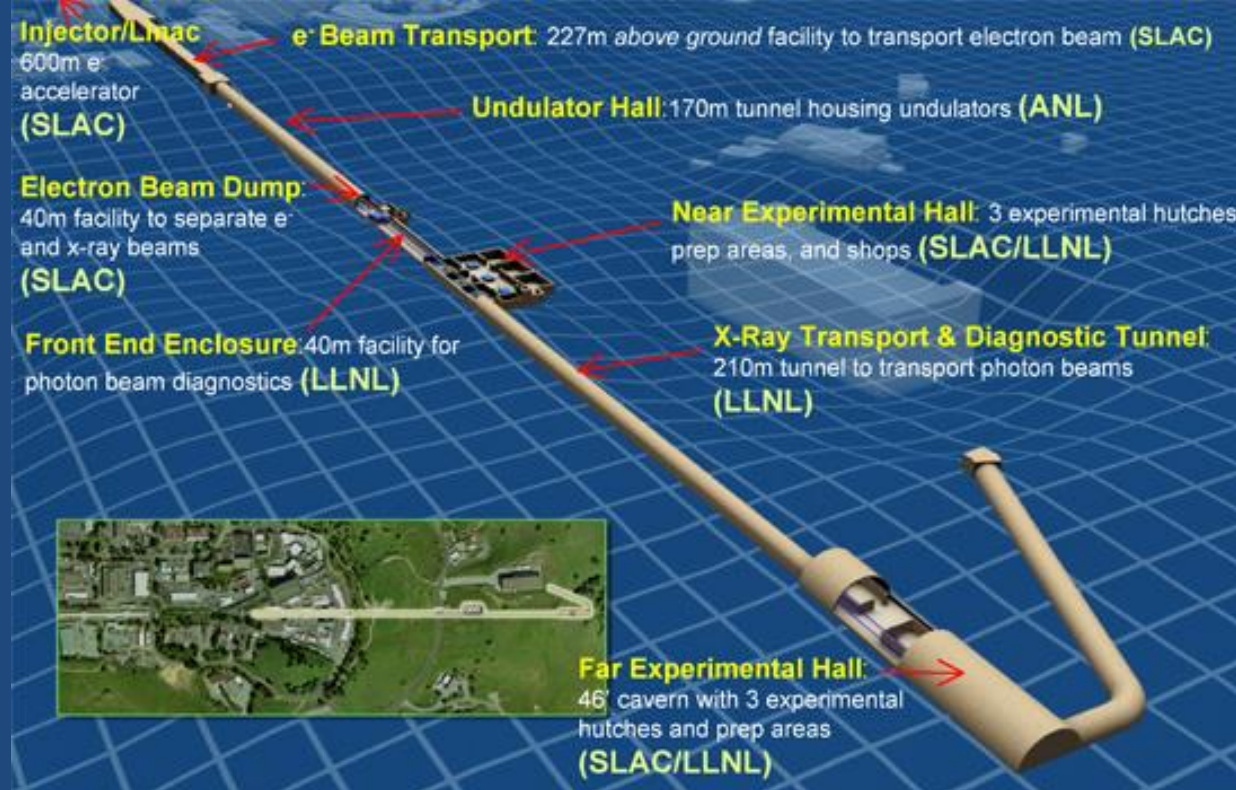
4^{th} Generation Light Source – Free Electron Laser

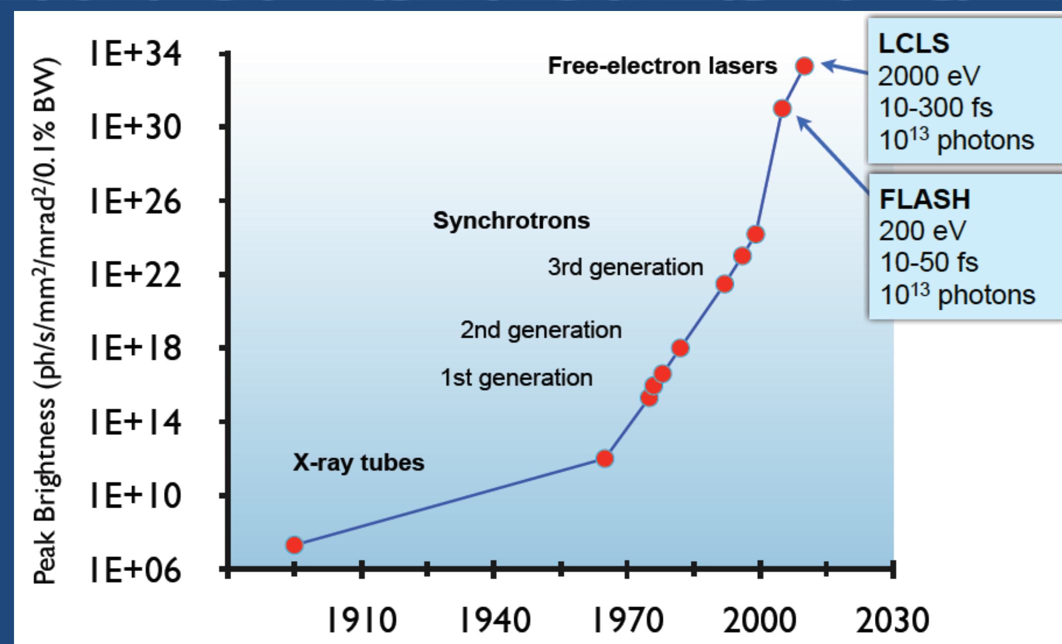


4th Generation Light Source –

X-ray FEL-

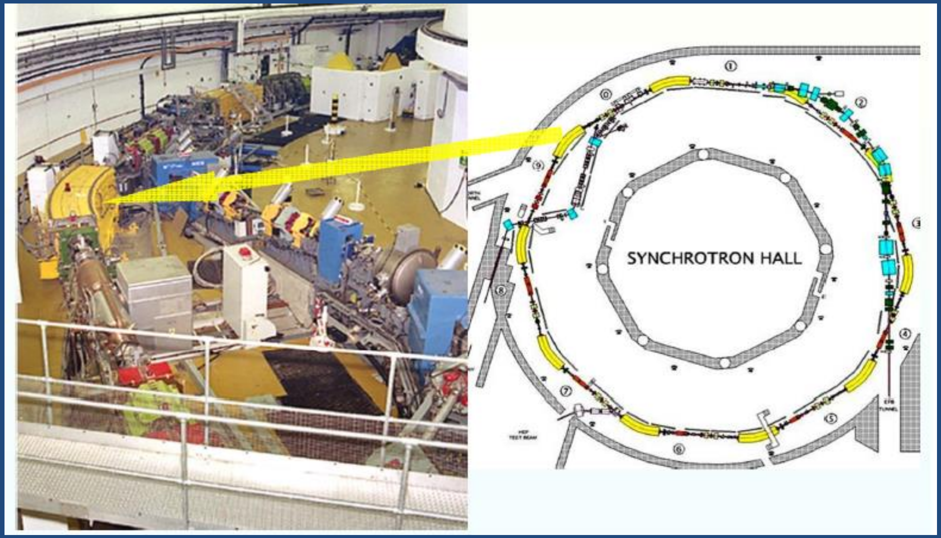
LCLS at SLAC





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 Spallation Facility (800 MeV) at RAL

+ new European Spallation Source (ESS) in Lund

AND FINALLY… PEOPLE POWER

CERN was founded 1954: 12 European States

"Science for Peace"

Today: 21 Member States

~ 2300 staff
~ 1600 other paid personnel
~ 10500 users

Budget (2014) ~1000 MCHF

Member States: Austria, Belgium, Bulgaria, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Israel, Italy, the Netherlands, Norway, Poland, Portugal, Slovakia, Spain, Sweden, Switzerland and the United Kingdom

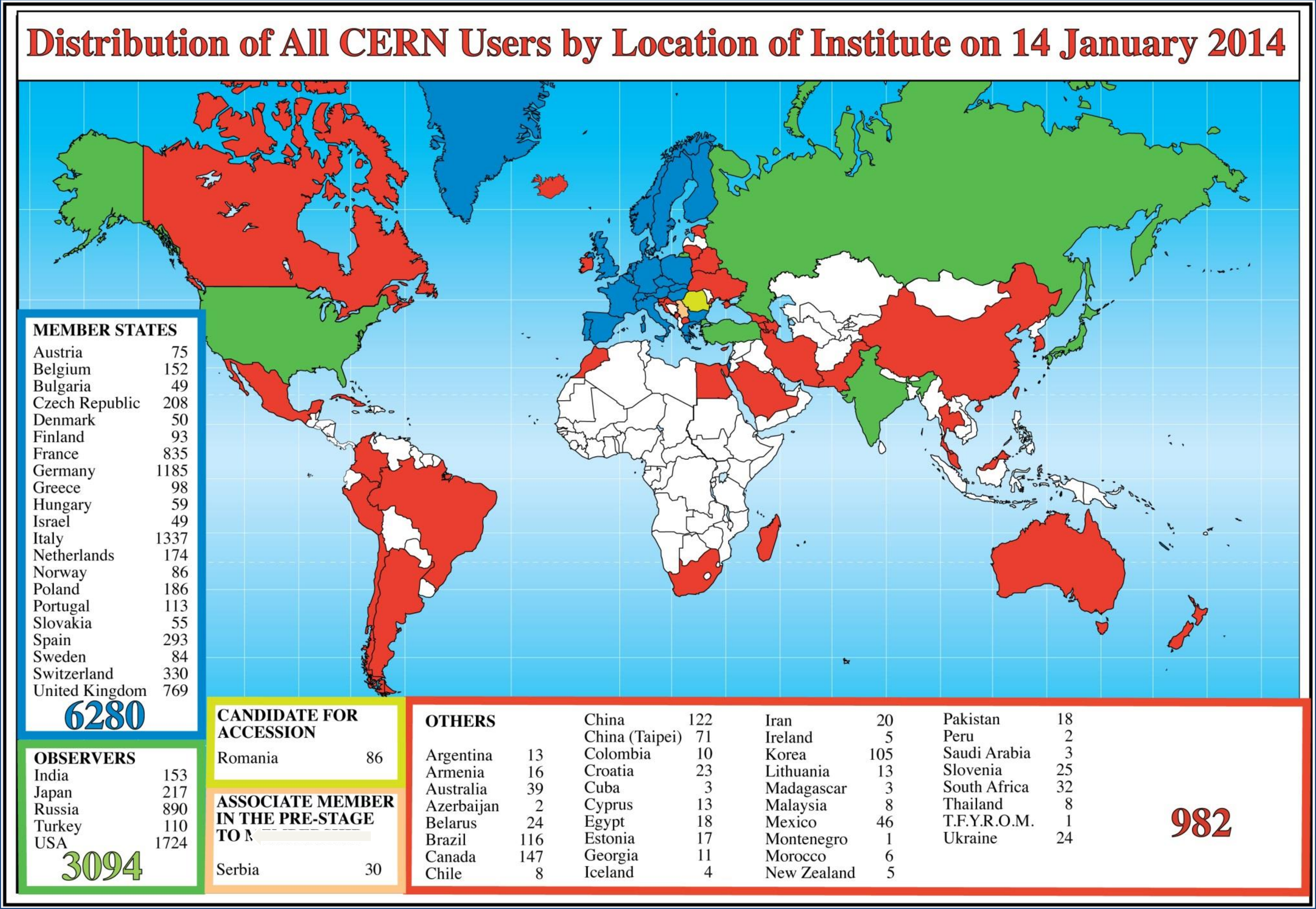
Candidate for Accession: Romania

Associate Member in Pre-Stage to Membership: Serbia

Applicant States for Membership or Associate Membership:
Brazil, Cyprus, Pakistan, Russia, Slovenia, Turkey, Ukraine

Observers to Council: India, Japan, Russia, Turkey, United States of America; European Commission and UNESCO

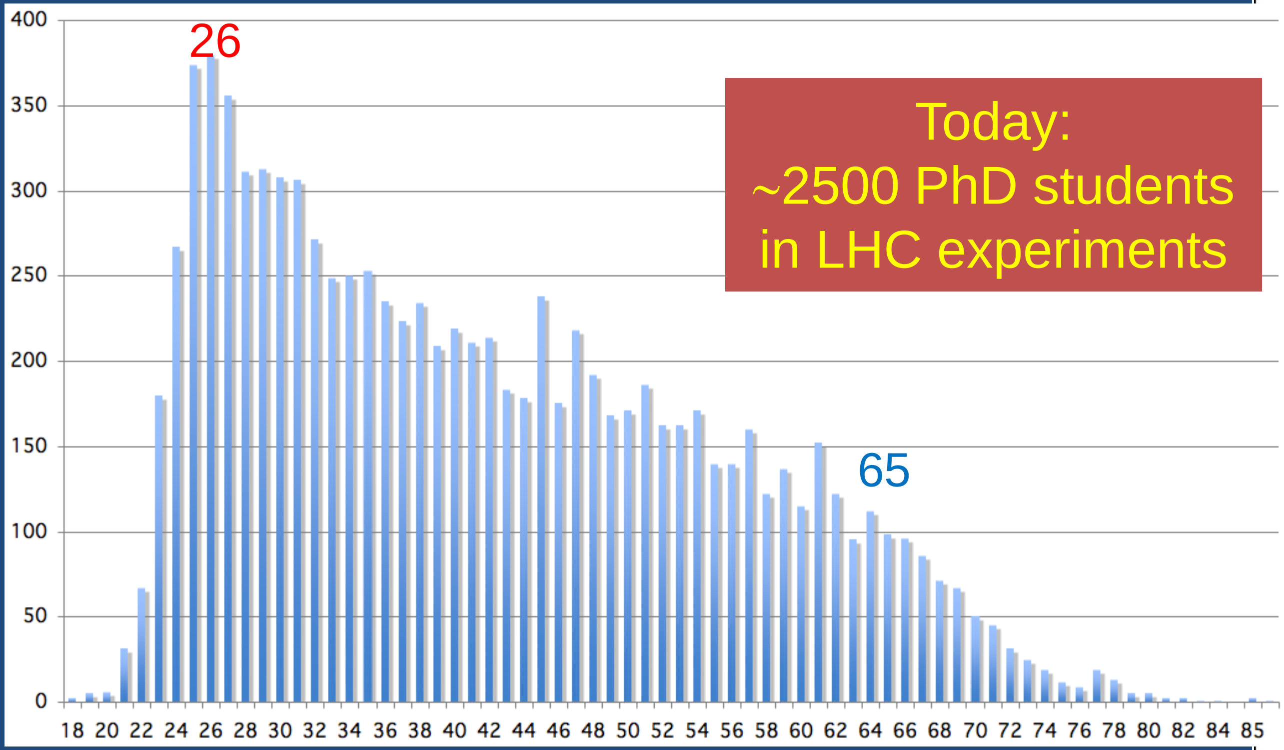
Science is getting more and more global



Age Distribution of Scientists

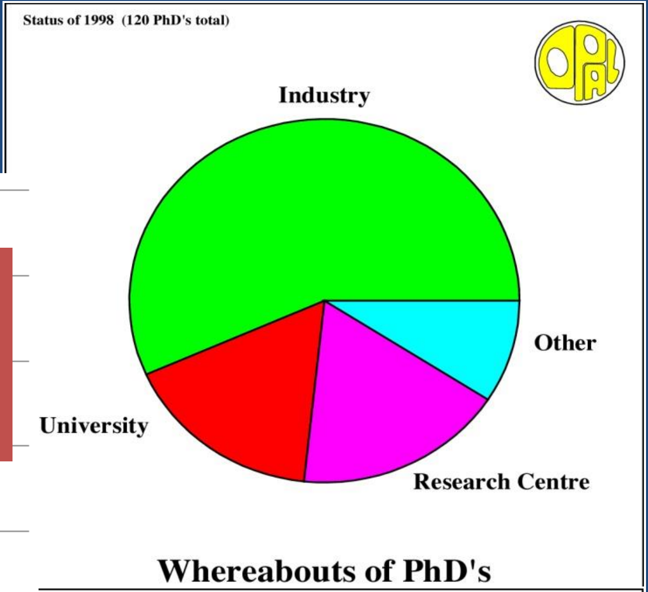
- and where they go afterwards

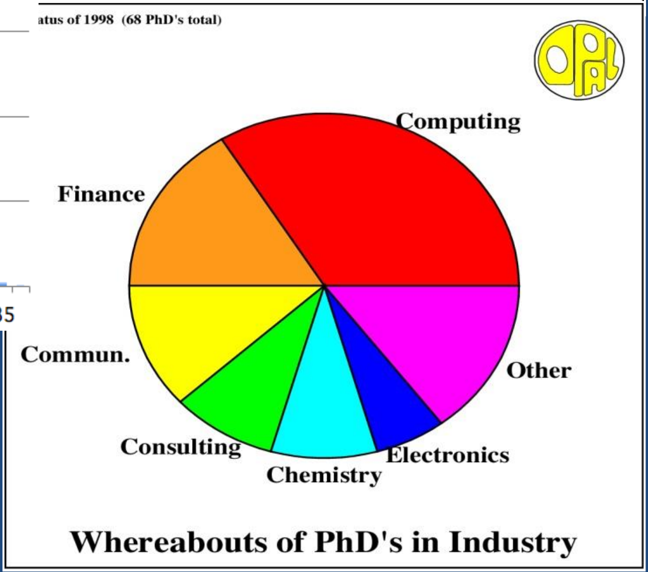
Survey in March 2009



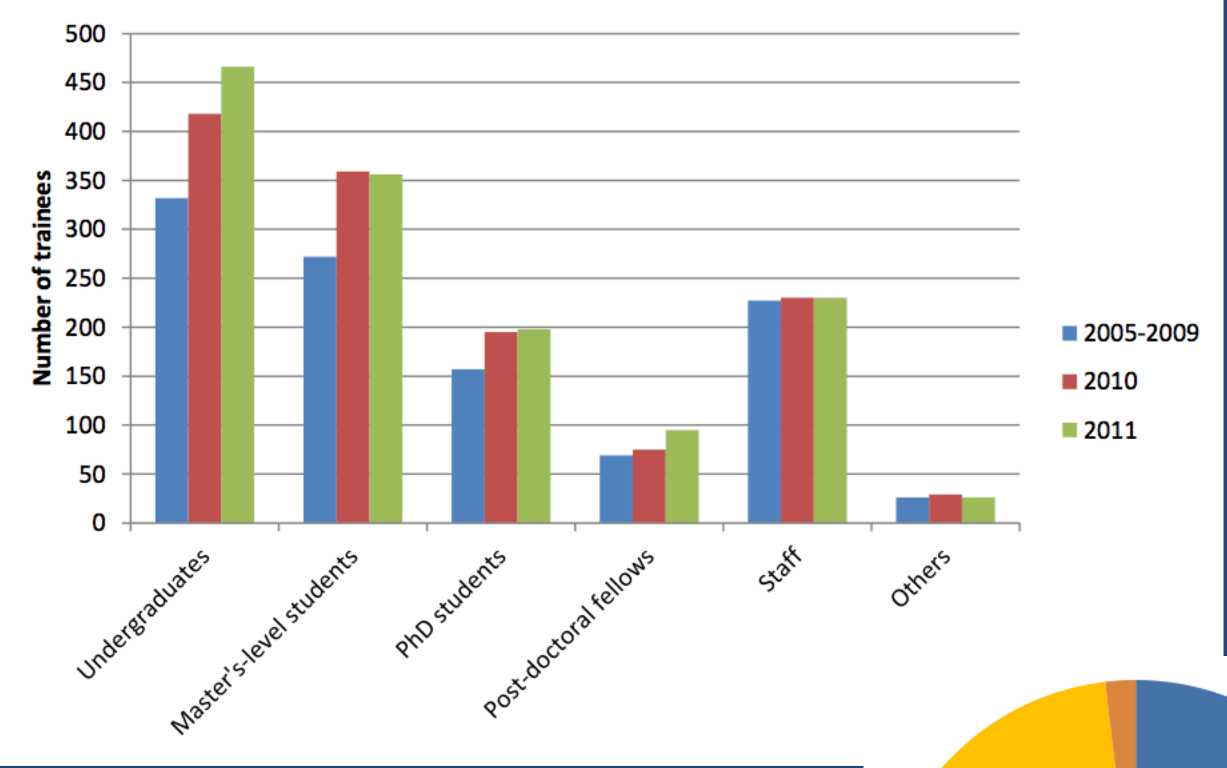
Today:
~2500 PhD students
in LHC experiments

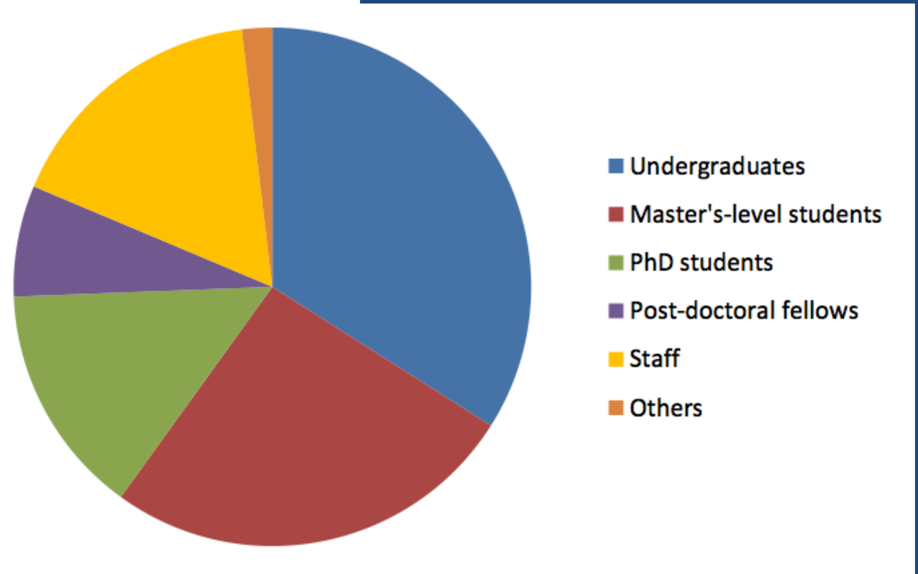
They do not all stay: where do they go?





Accelerator Science Training in Europe

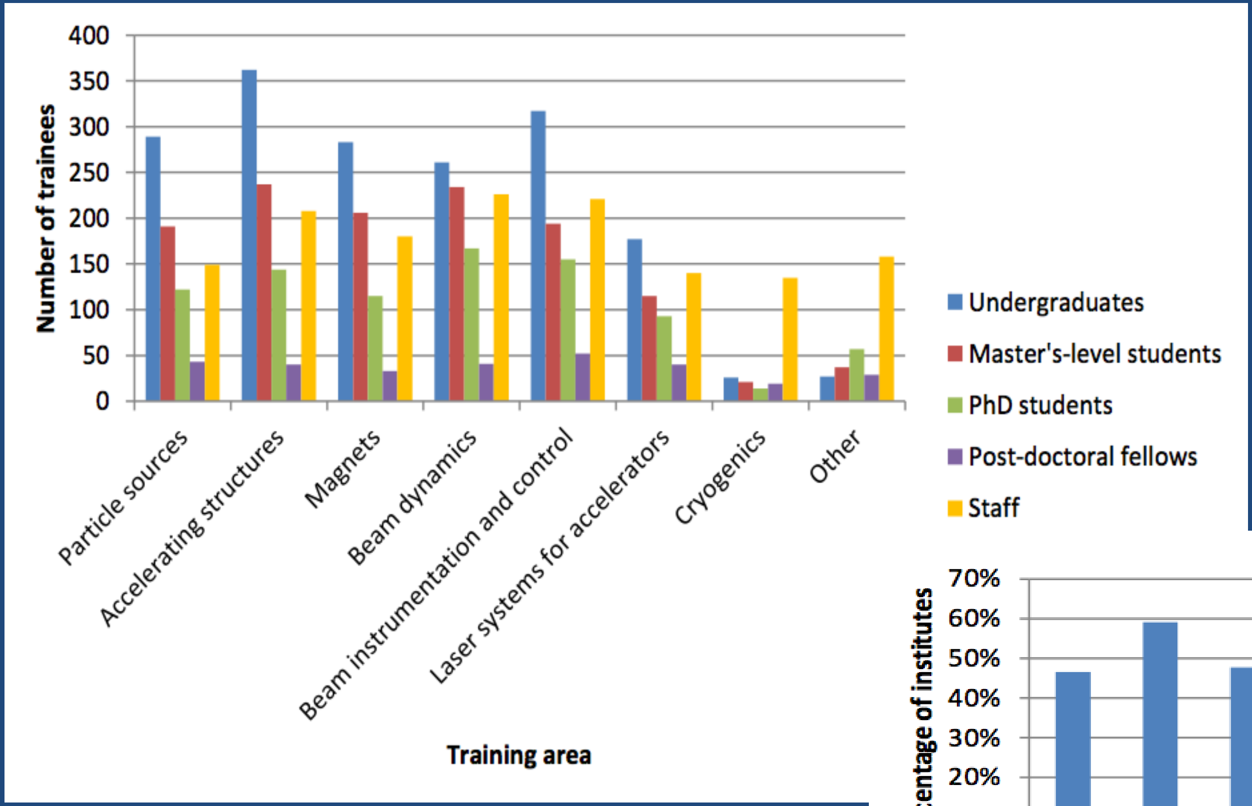


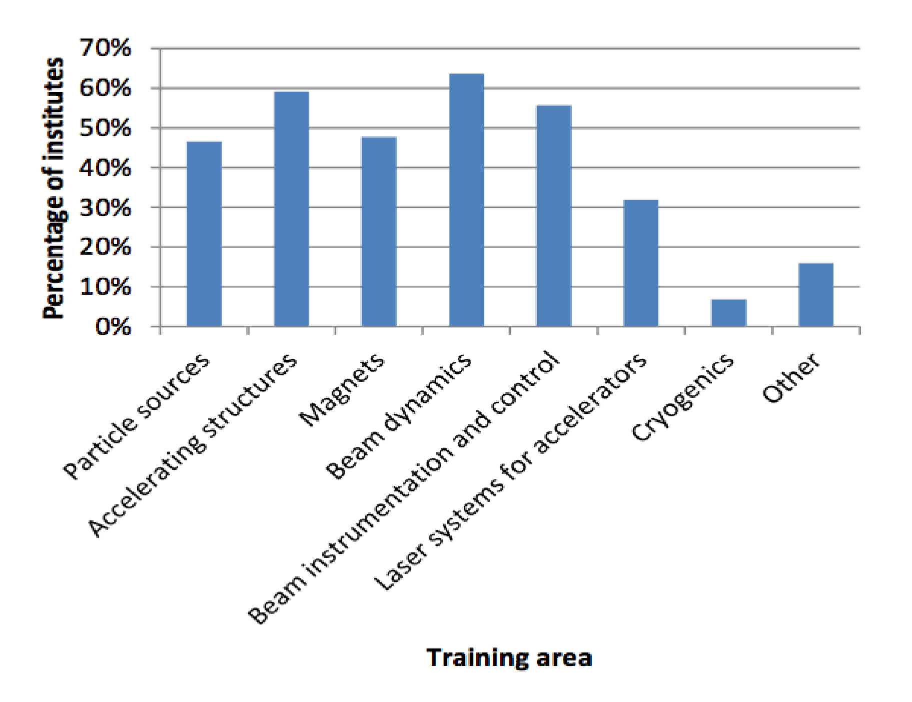


TIARA Work Package
Education and Training in Europe

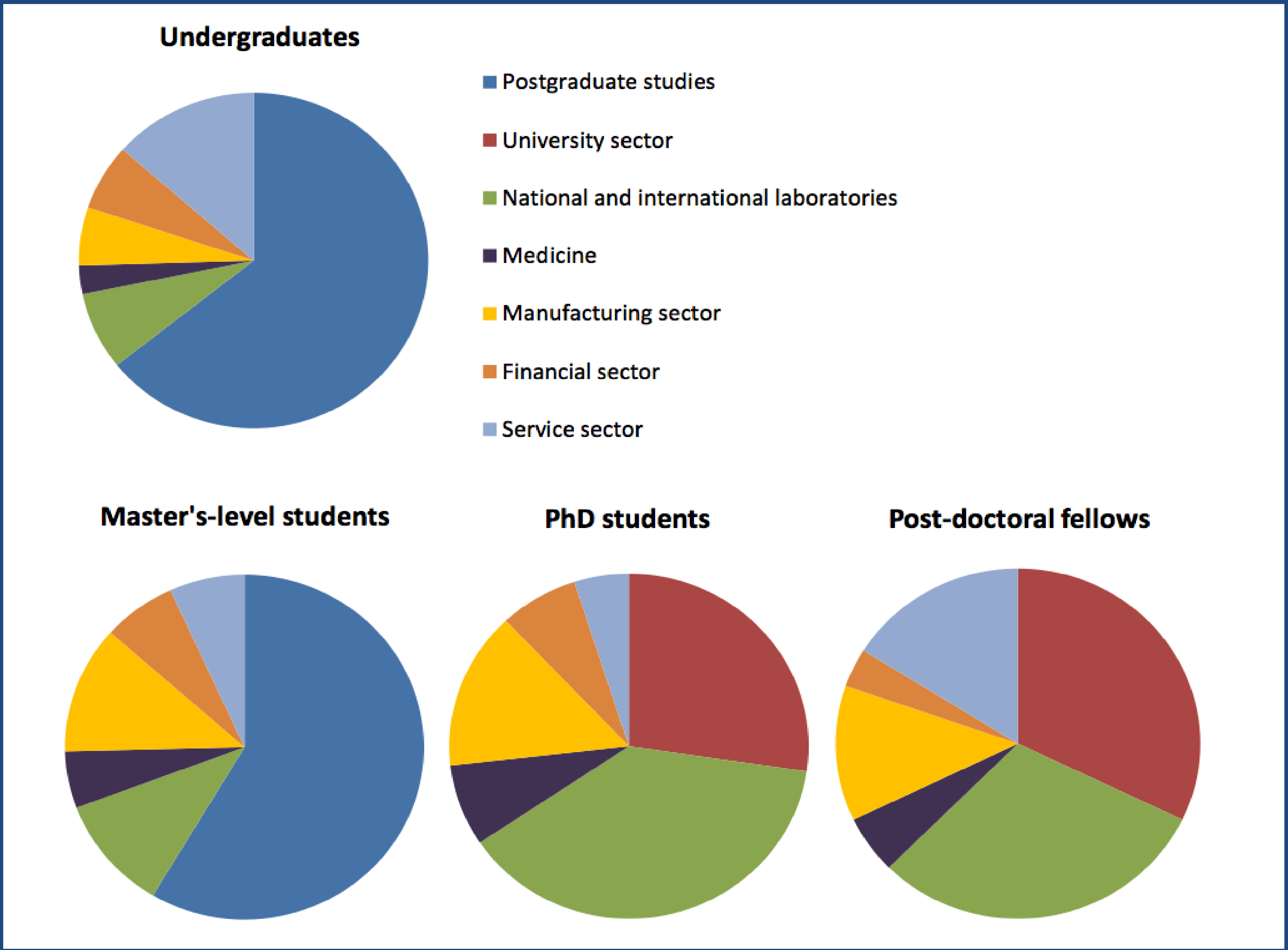
http://www.eu-tiara.eu/database

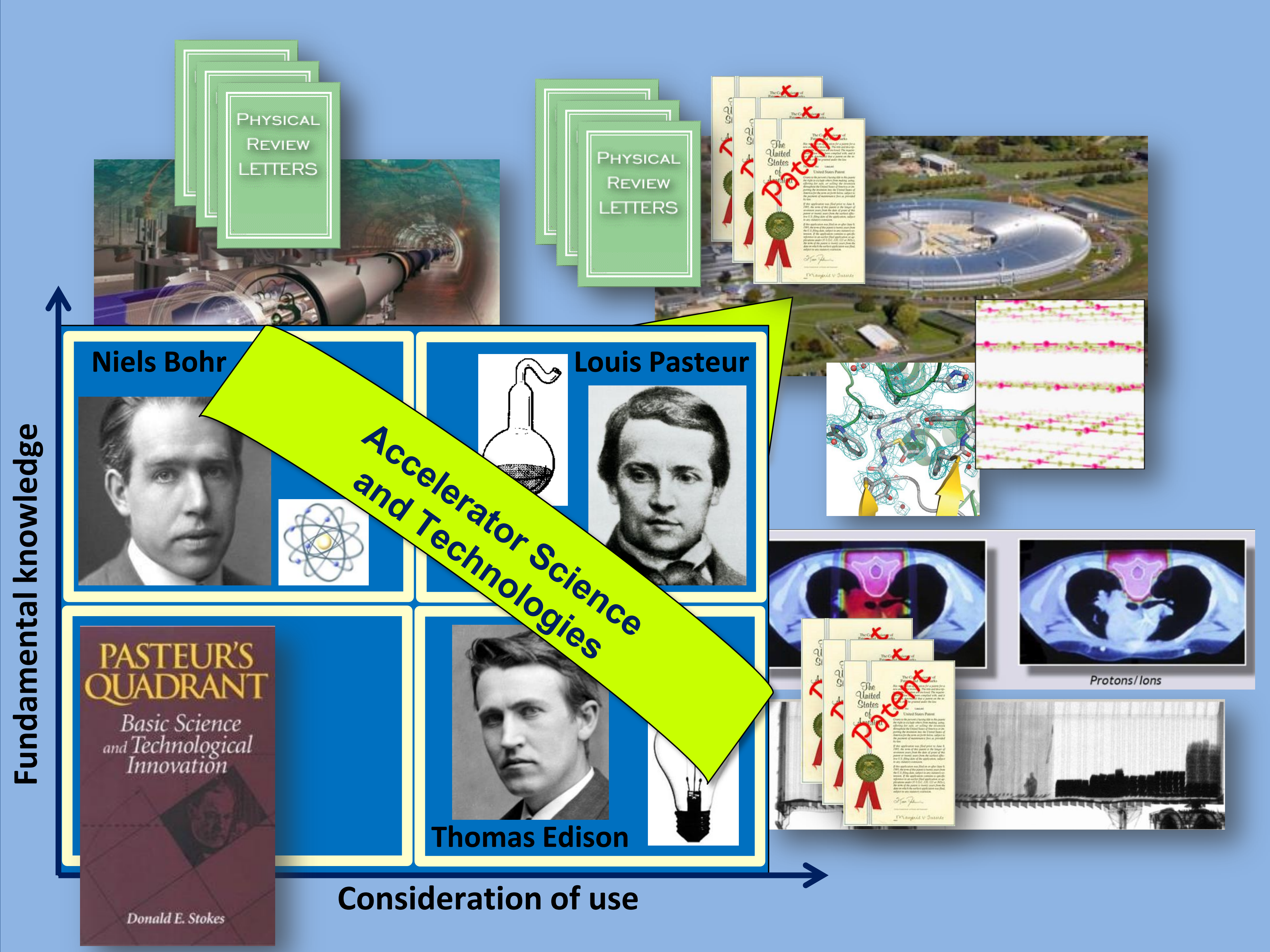
Accelerator Science Training in Europe





Career Destinations for Accelerator Scientists





Physical Review Letters
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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