"Accelerating Medical Knowledge: Sharing for a Sustainable Future"

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European Spallation Source
(Afterwork: APS, ASP, IUPAP)

Innovation for Fostering in Accelerator Science and Technology (I.FAST)
Challenge Based Innovation 2024: **Accelerators for healthcare**

16 / 07 / 2024

Outline

Context of Accelerators for healthcare

Selected Courses and Colloquia Suggestions

Accelerator for Innovation in Life Science

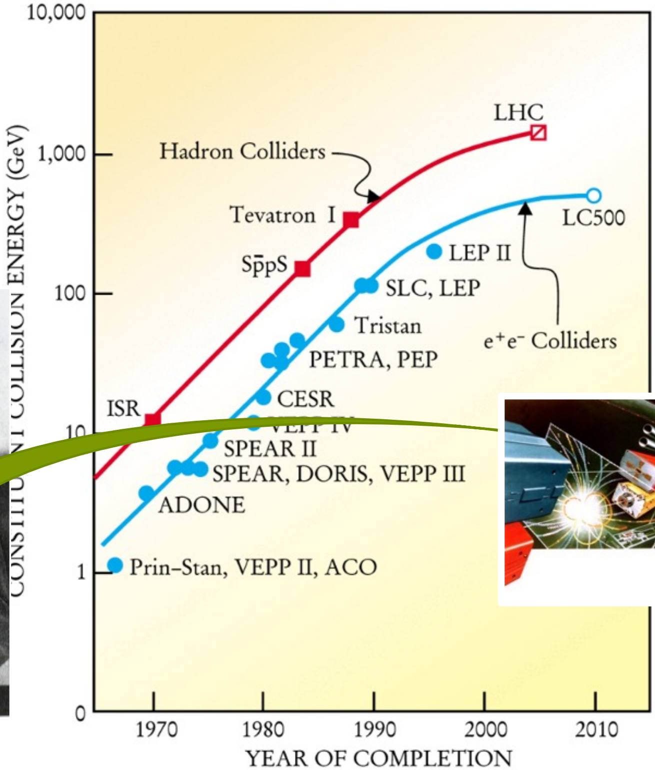
Context of Accelerators for healthcare

Science Context and Particle Accelerators

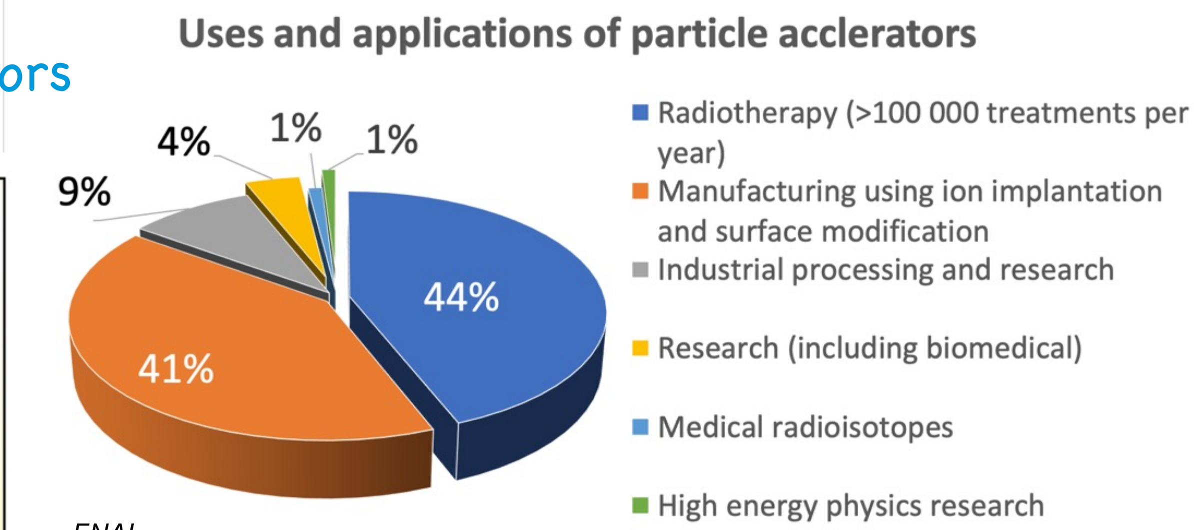
More than 35,000 Particle Accelerators in the world ! (15.000 in 2000)

Ernest Lawrence
(1901 - 1958)

80 keV
1929



Livingston's diagram

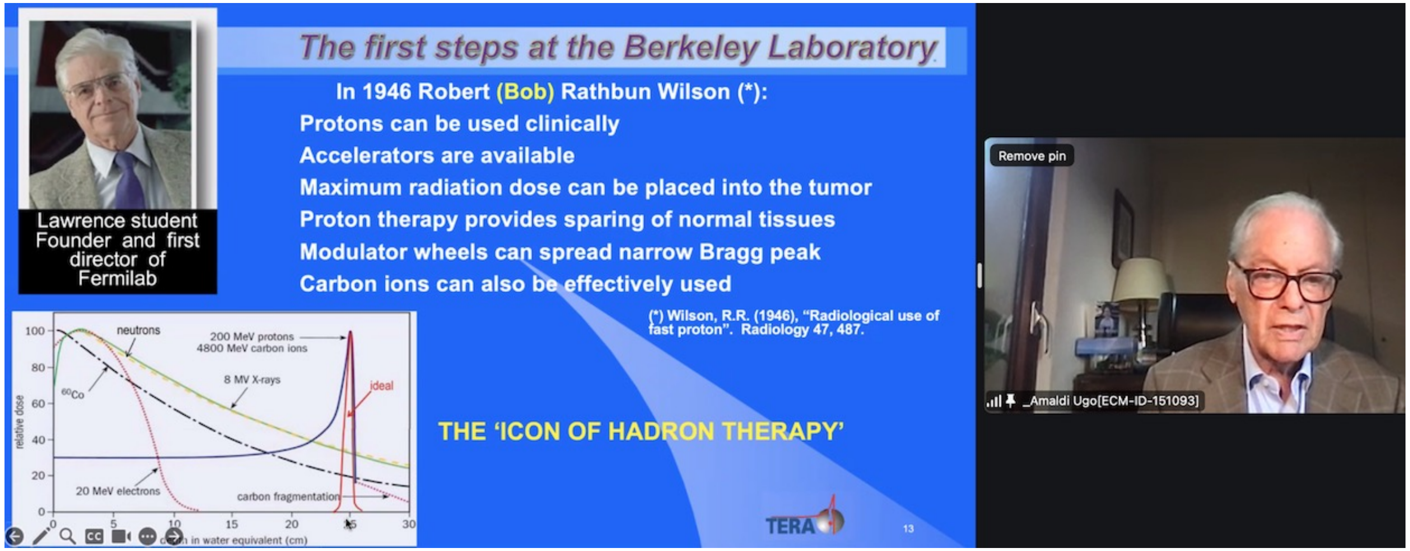


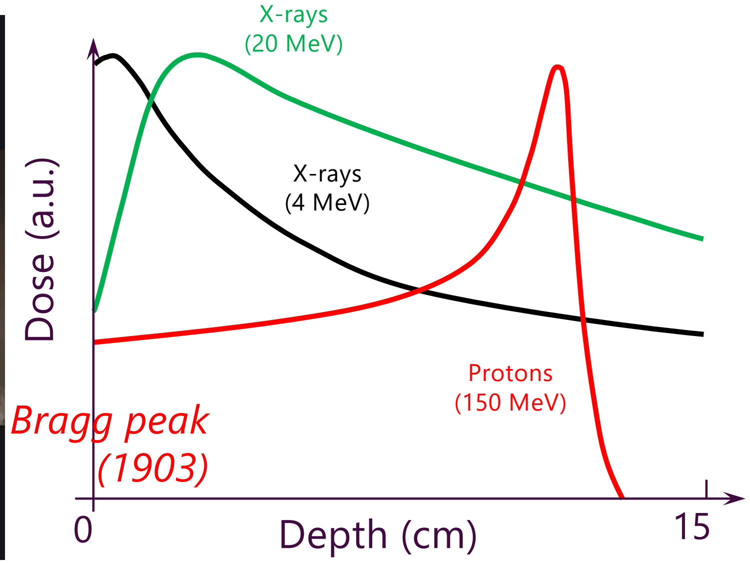
FNAL

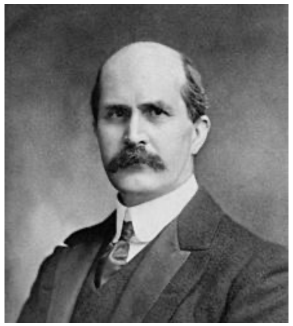
→ 1980 -Tevatron @ Fermilab 980 GeV

→2008 - LHC @ CERN 7-14 TeV

Radiation Therapy elements







W.H. Bragg (1862-1942)
Nobel Prize in Physics
1915

The Bragg peak is a pronounced peak on the Bragg curve which plots the energy loss of ionizing radiation during its travel through matter.

The discovery of Bragg's law in 1913 by William Henry Bragg and his son William Lawrence Bragg provided a fundamental understanding of how X-rays interact with crystal structures, leading to numerous breakthroughs in determining the atomic and molecular structures of materials.

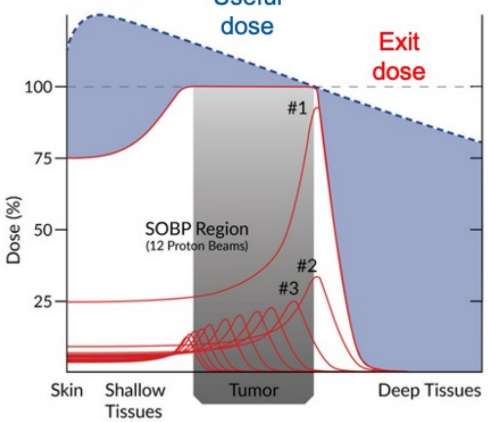
The Braggs (father&son) won the Nobel Prize in Physics in 1915!

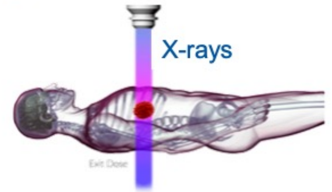
William Lawrence Bragg: 1st pre. of the International Union of Pure and Applied Physics (IUPAP)

Radiation Therapy elements

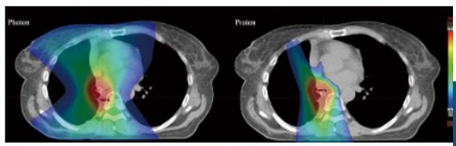
See more applications:
“GaToroid A Toroidal Gantry for Particle Therapy”
Luca Bottura, 29 May 2024

Hadrons vs. photons





X-rays Protons



SOBP: Spread Out Bragg Peak

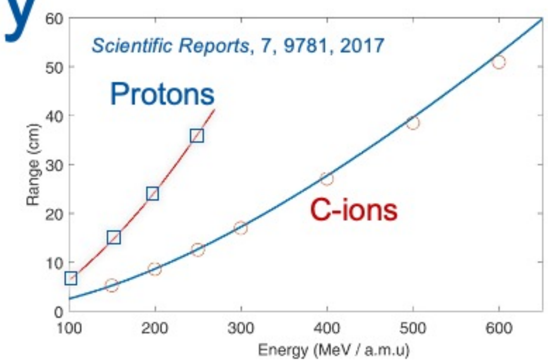
Translational Lung Cancer Research, 6(2), 2017

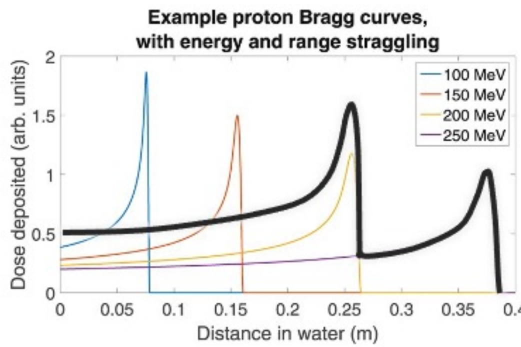
GaToroid

Graphics by courtesy of Protom

Ranges of energy

- The depth of the Bragg peak depends on the particle type and its energy
- The typical energy range required to reach deep seated tumors is about 50…250 MeV for protons, and 100…500 MeV/u for carbon ions (to be compared to 2…20 MeV for photons)
- **The effect of beams of different energies can be superposed to deposit partial doses and treat tumors over a given depth**





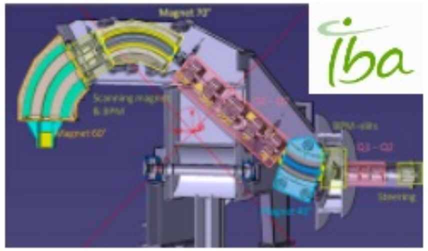
GaToroid

Radiation Therapy elements

Gantries – bulky precision objects

protons

Length = 10.5 m
Diameter = 10 m
Weight = 270 tons



Length = 9.5 m
Diameter = 7.2 m
Weight = 110 tons

Length = 10 m
Diameter = 8 m
Weight = 17 tons(*)

ions

Length = 25 m
Diameter = 13 m
Weight = 670 tons

Length = 13 m
Diameter = 10 m
Weight = 350 tons

Length ≈ 9 m
Diameter ≈ 9 m
Weight ≈ 240 tons

Radiation Therapy elements

Courtesy of CERN KT and E. Felcini, CNAO

"GaToroid is meant to be lightweight: if used with proton beams, the structure would have an outer diameter of about 3.2m, for a total weight estimated around 12 tons. For carbon ion beams, the outer diameter would be of the order of 5m, for a total weight of around 50 tons. This represents a substantial weight reduction compared to conventional gantries, which weights around 100 tons for protons and over 350 tons for carbon ions."

GaToroid: An interesting project…

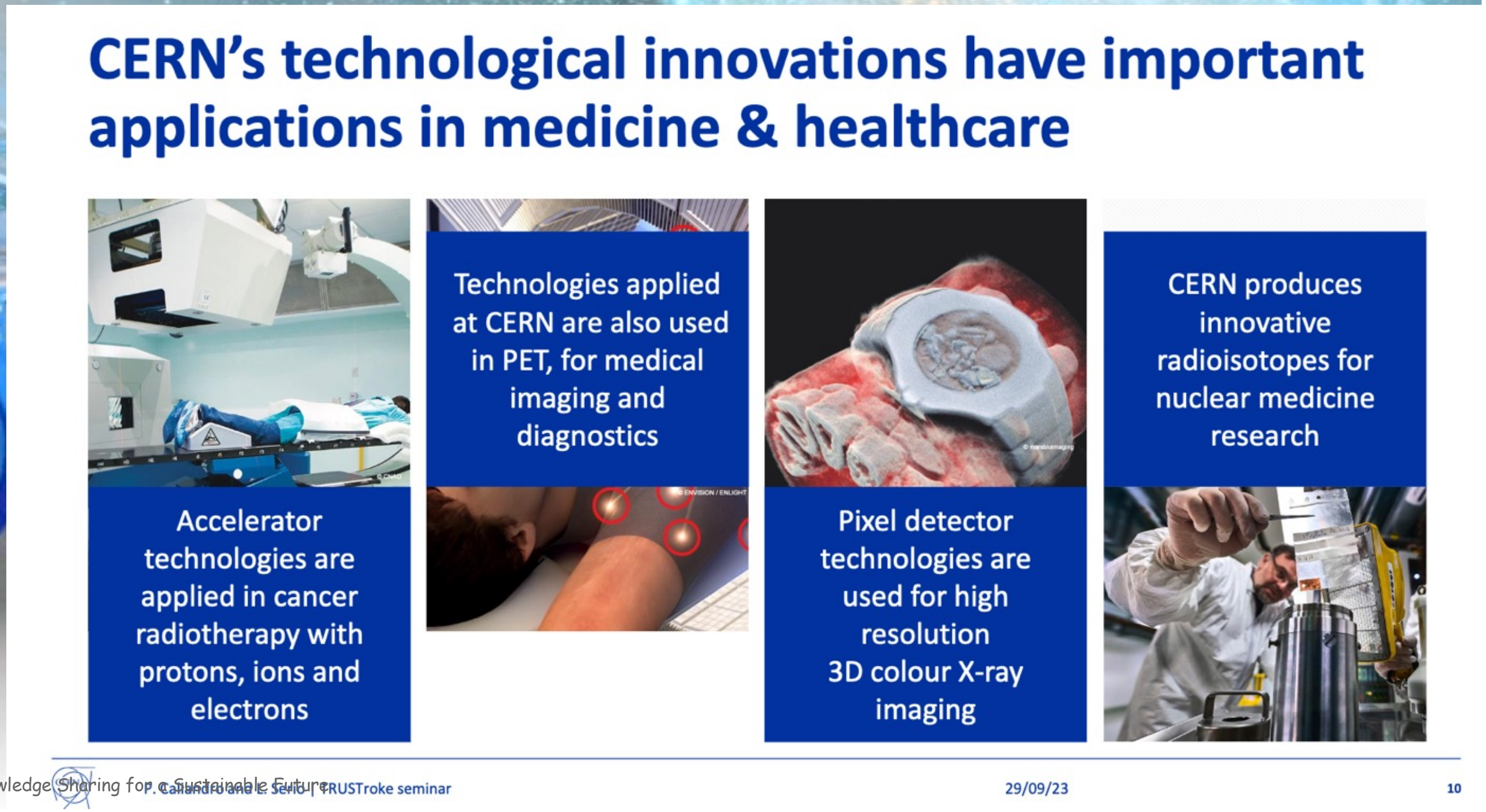
CERN as a Model for Knowledge Transfer

- CERN Accelerating science - Accélérateur de science (2022)

- Impact of CERN technologies: from fund. research to our everyday lives (2023)

"Social Cost Benefit Analysis of HL-LHC"

CERN70 @APS – movie – 15'



Anniversary Celebration at CERN

Live broadcast:

- CERN70 website
- CERN's YouTube and LinkedIn channels

Discover more at https://cern70.cern

Knowledge Transfer

https://indico.cern.ch/event/1382946/

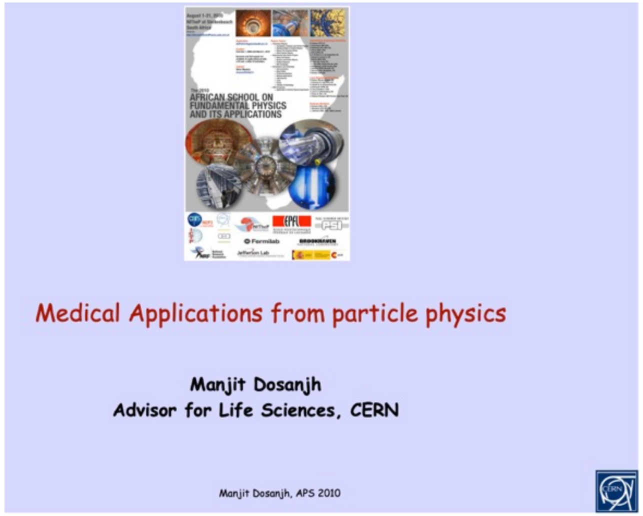
The event, "**From Particle Physics to Medicine**," on March 7th, 2024, provides an opportunity to explore the diverse applications of particle physics instruments and tools in hospitals and medical research, showcasing how this field is advancing innovative medical technologies:

- **"Accelerators to treat cancer"**
- **"Looking inside the human body"**
- **"The digital health revolution"**

Knowledge Transfer

MediPix

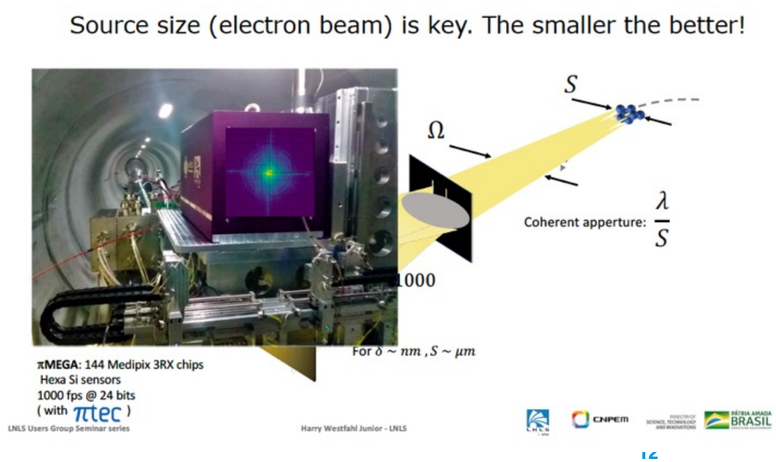
Medipix is a family of read-out chips for particle imaging and detection developed by the Medipix Collaborations.



from: Manjit DOSANJH (CERN) – August 2010:

"*Medical Applications from particle physics*" ASP2010

African School of fundamental Physics and Applications



to: Harry Westfall (SIRIUS) – August 2021:

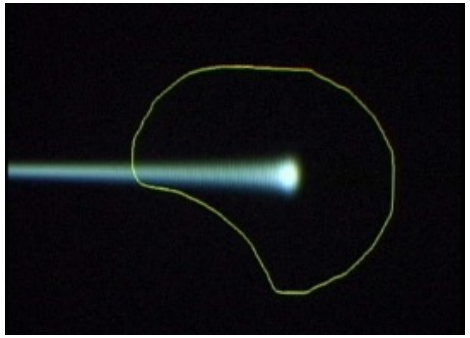
"*Sirius: The New Bright Lights to Science from the Southern Hemisphere*"

Forum on International Physics (FIP) – Colloquia series

European Network for Light Ion Hadron Therapy (ENLIGHT)

Courtesy Manjit Dosanjh, ENLIGHT Coordinator
CERN/University of Oxford

ENLIGHT was established to ………

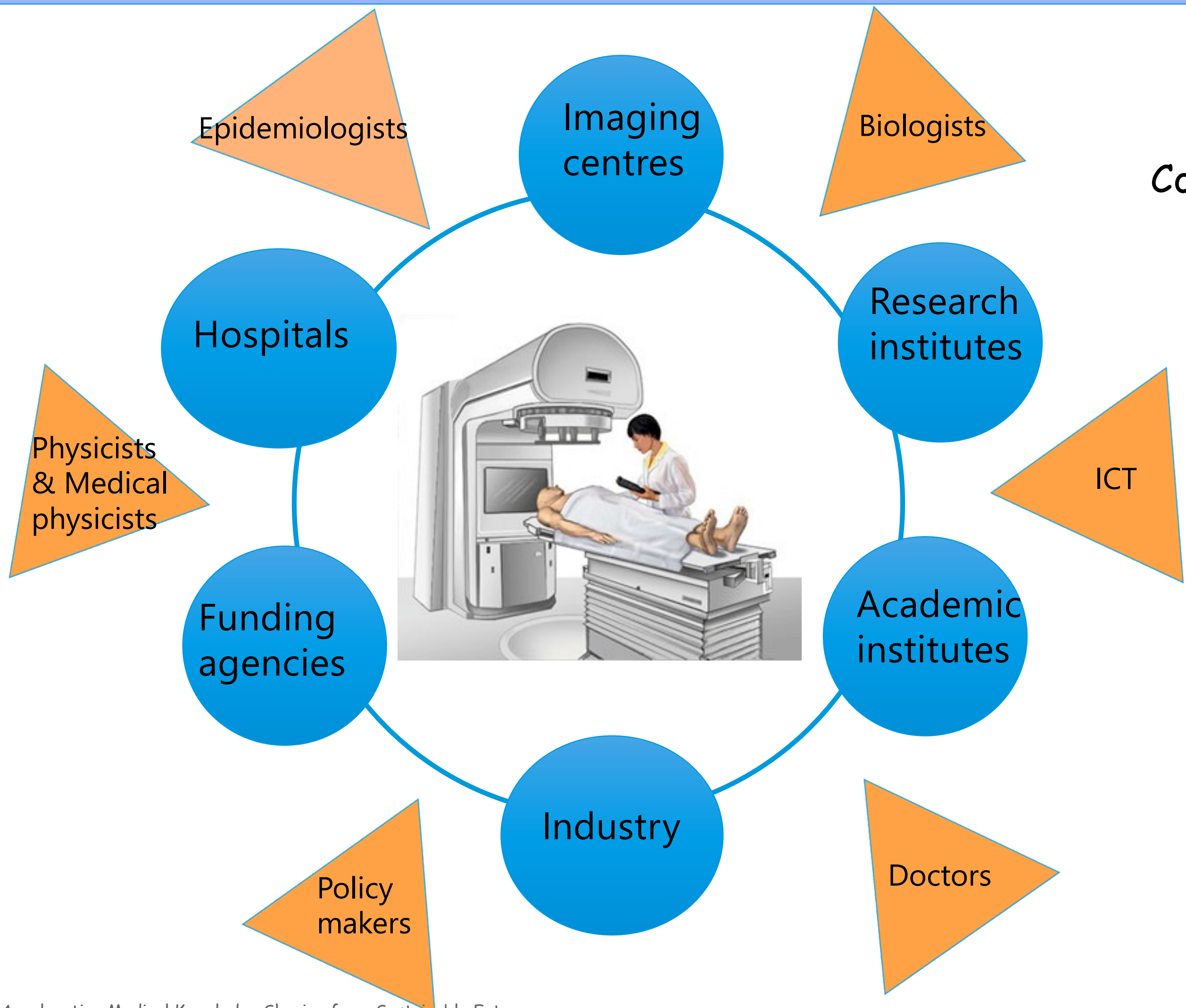


- Create common multidisciplinary platform
- Cancer treatment
- Identify challenges
- Share knowledge
- Share best practices
- Harmonise data
- Provide training, education
- Innovate to improve
- Lobbying for funding

Leveraging Physics collaboration philosophy into a multidisciplinary medical environment

ENLIGHT: collaboration is key

Courtesy Manjit Dosanjh

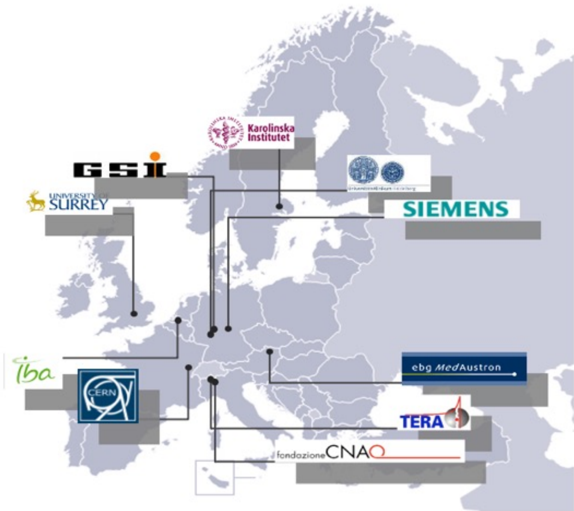


ENLIGHT

Courtesy Manjit Dosanjh

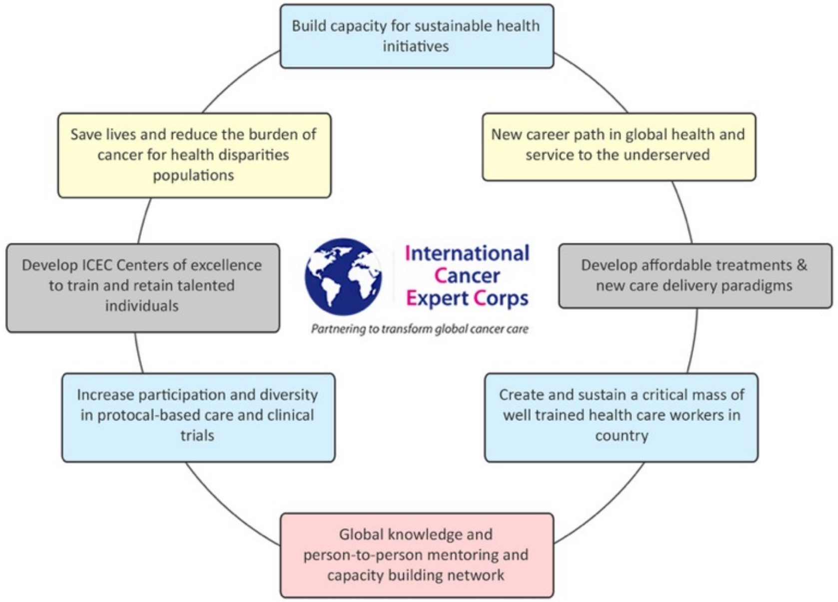
PARTNER – a success story

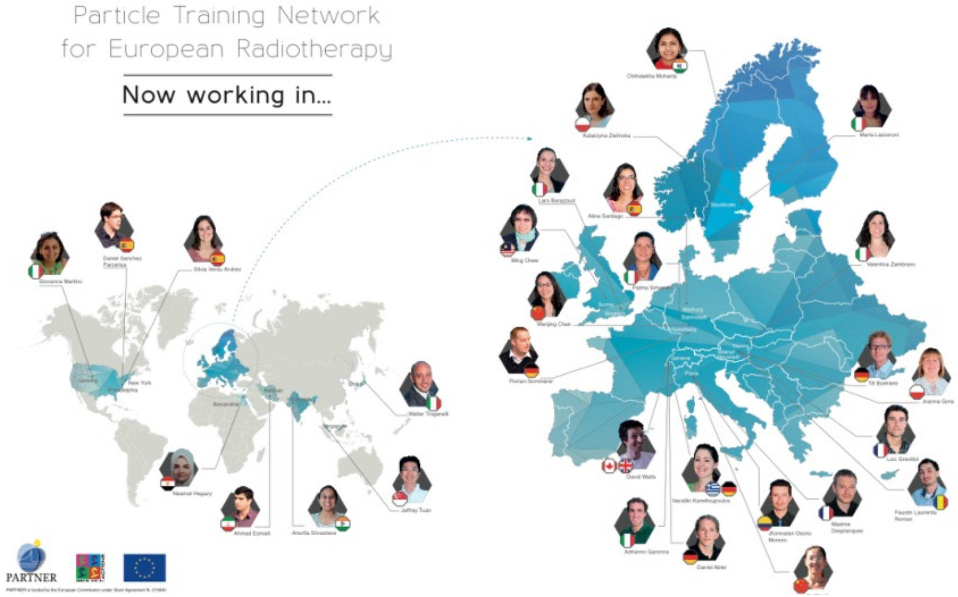
- Particle Training Network for European Hadrontherapy
- 10 academic institutes, research centres, 2 leading companies
- 29 young researchers



Outcome :

- Now working around the World
- 7 at Medaustron
- Open access PARTNER-JRR





International Cancer Expert Corps (ICEC) and STELLA

Project STELLA (Smart Technologies to Extend Lives with Linear Accelerators)

The Project STELLA is dedicated to:

- Expanding access to high quality cancer treatment globally
- Developing an innovative and transformative radiation therapy treatment system
- Driving down the cost out of RT and cancer care
- An enhanced training, education and mentoring program that catalyzes RTT implementation in the global context

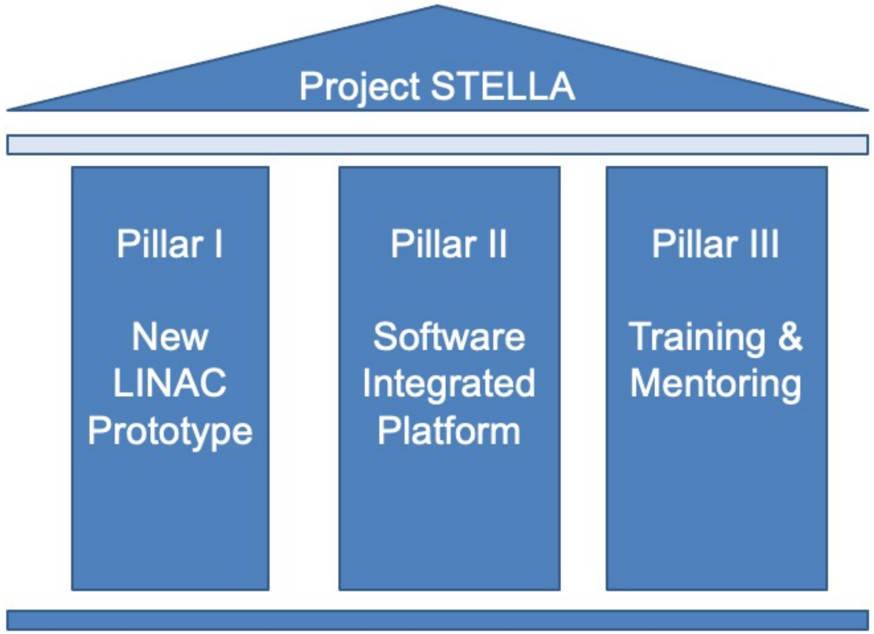
the international arena

ICTR-PHE 2014

"Developing medical linacs for challenging regions"

by David Pistenmaa and Norman Coleman, International Cancer Expert Corps, Inc., and Manjit Dosanjh, CERN

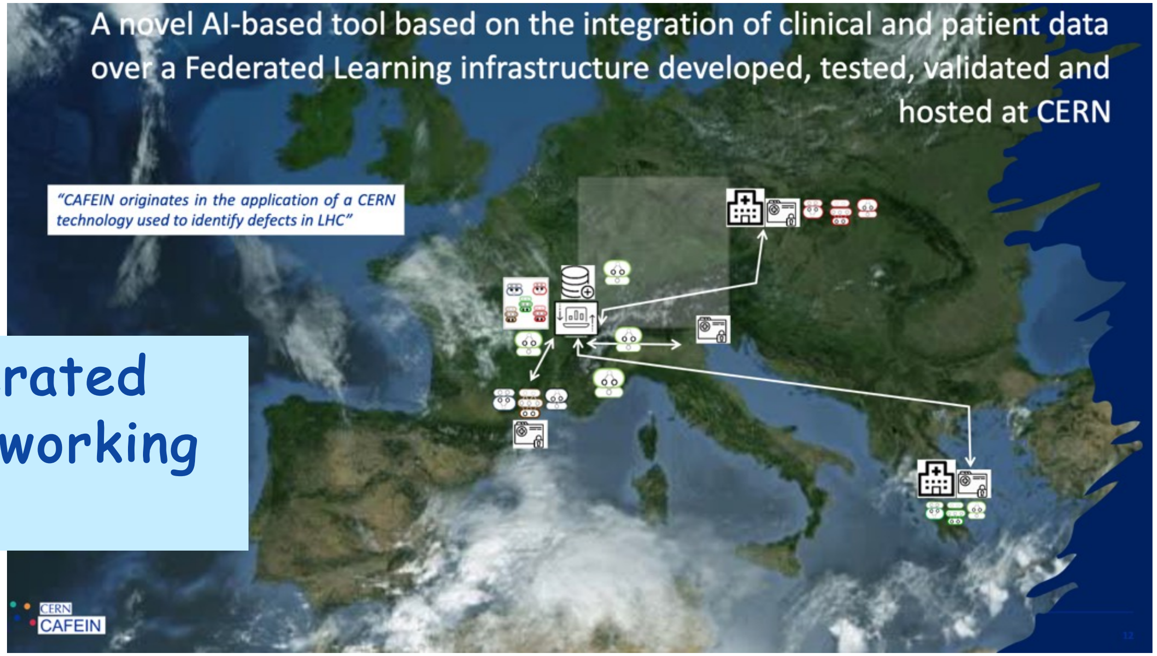
STELLA: A Unique Collaboration



Accelerator Data

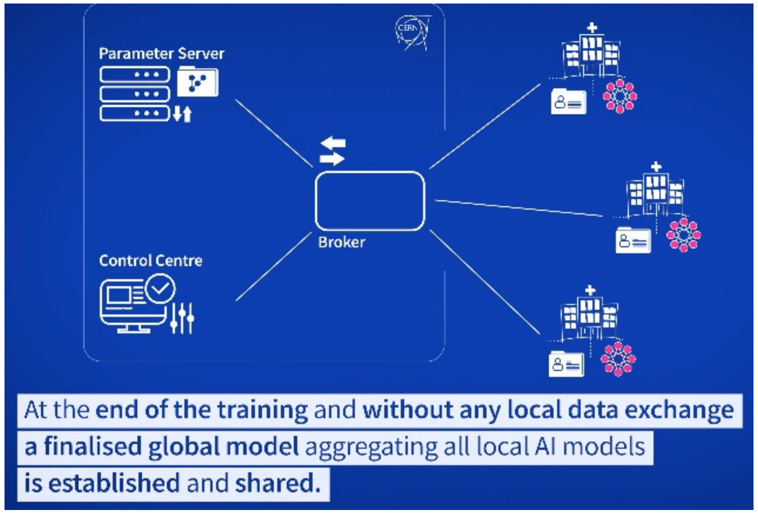
Courtesy Luigi Serio

Computational Algorithms for Federated Environments: Integration and Networking (CAFEIN)



Video: https://cafein.web.cern.ch/Technology

A Federated Learning (FL) platform, called CAFEIN*, based on artificial intelligence (AI) algorithms, was developed at CERN in order to ensure immense precision in the operation of the complex system of the accelerator chain.



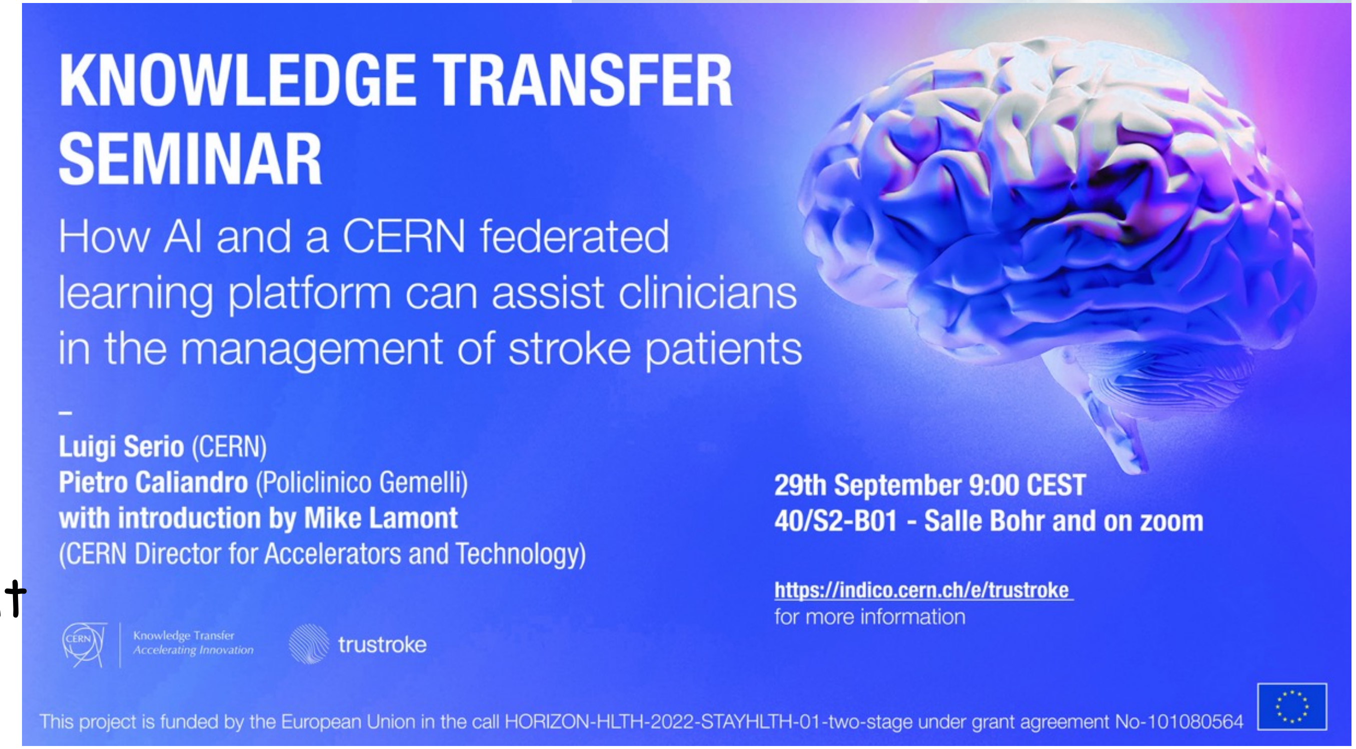
Project: TRUSTroke webinar on Federated Learning: https://indico.cern.ch/e/trustrokewebinar

Accelerator Data

"Accelerating stroke prevention", 13 sep, 2023

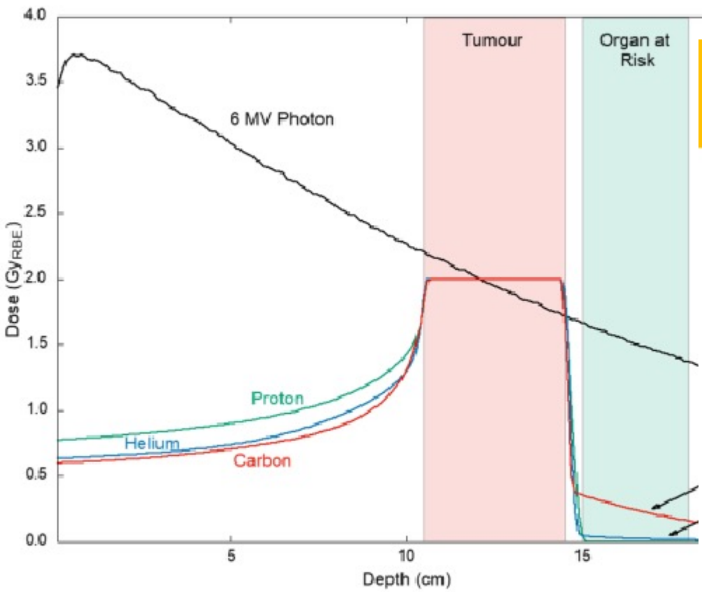
https://indico.cern.ch/e/trustroke

AI and CERN federated learning to assist clinicians. CAFEIN, originally designed for spotting anomalies in the CERN accelerator chain operation can also be used in healthcare, in the management of stroke patients.



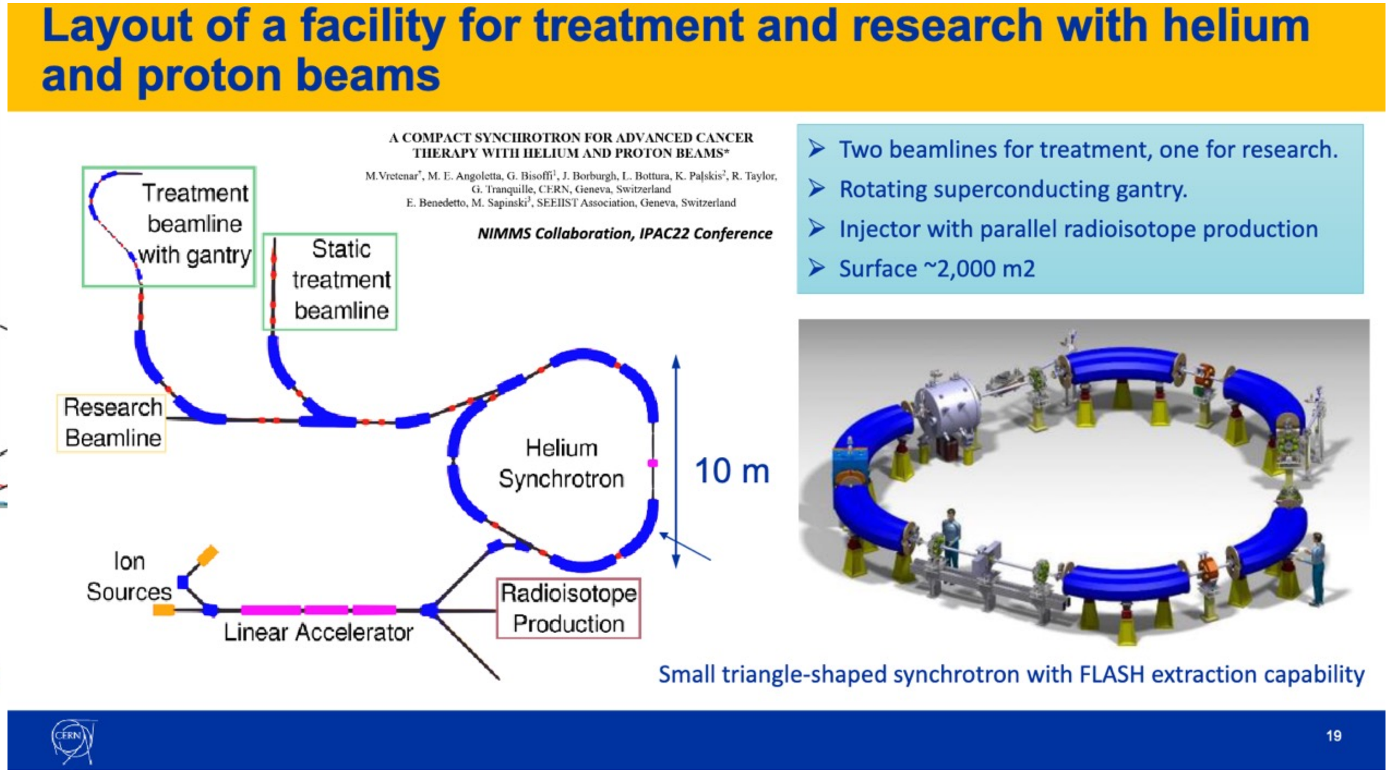
More CERN initiative for Cancer Therapy

(NIMMS): "Next Ion Medical Machine Study: fighting cancer with accelerators" by Maurizio Vretenar



Spread-out Bragg peak for proton, helium, carbon compared to X-rays

(K. Kirkby et al., Heavy Charged Particle Beam Therapy and related new radiotherapy technologies, https://doi.org/10.1259/bjr.20200247)



More CERN initiative for Cancer Therapy

South East European International Institute for Sustainable Technologies (*SEEIIST*)

Proposed in late 2016 by Prof. Herwig Schopper, a former Director General of CERN and initiator of the international SESAME project in Jordan, received first official political support by the Government of Montenegro in March 2017.

SEEIIST is a collaborative initiative among South-East European states to establish a cutting-edge research infrastructure focused on accelerator-based cancer therapy and biomedical research, with strong regional and international support, aiming to foster scientific cooperation, economic development, and social cohesion in the region.

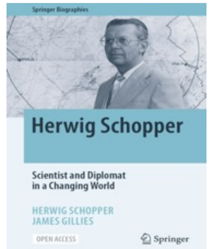
Register to the LIFE Virtual PHYSICS MATTERS Colloquium on Aug. 29

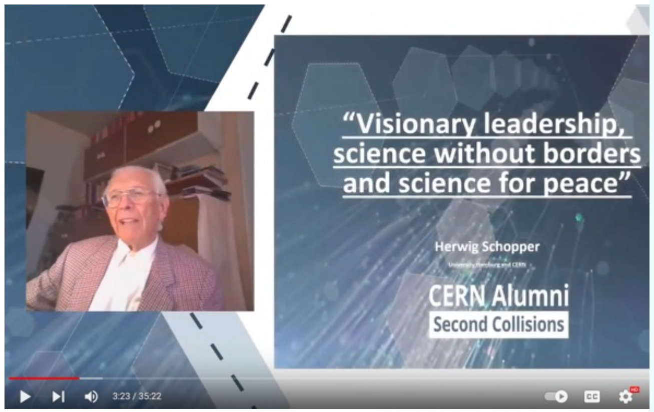
"Beating Cancer with SEEIIST while Shaping Science in South-East Europe"

by Sanja Damjanovic, former Minister of Science in the Government of Montenegro

Bringing Light !!

[Book Open Access: Herwig Schopper Scientist and Diplomat in a Changing World]

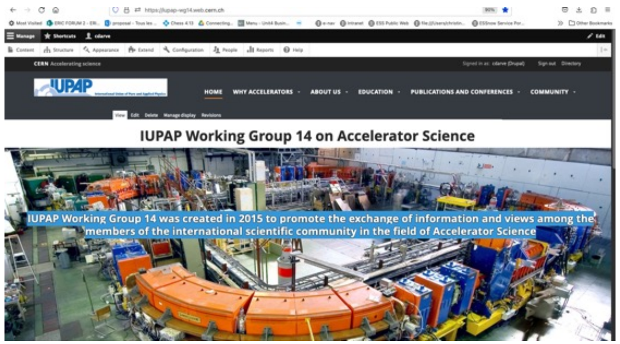




Courses and Colloquia Suggestions

Knowledge Sharing - Suggestions

- Massive Open-Online Courses:
  - MOOC & school Nordic Particle Accelerator Project
  - MOOC Accelerate Your Teaching (incl. SiS)



- African School of Fundamental Physics and Applications (ASP)
- FASEM - Scattering technology Advanced school
- PHYSICS MATTERS Online Colloquia Series by FIP at APS
- Int. Union of Pure and Applied Physics (IUPAP) WG14

Massive Open Online Courses for Accelerators

Nordic Particle Accelerator Project (NPAP)

Existing educative platforms and programs:

✓Accelerator schools: **JUAS, CAS, HASCO, USPAS, ACAS, ASP, etc**

✓University programs (e.g. Aarhus, LU)

✓EU-TIARA market surveys

✓EU-ARIES and I.FAST

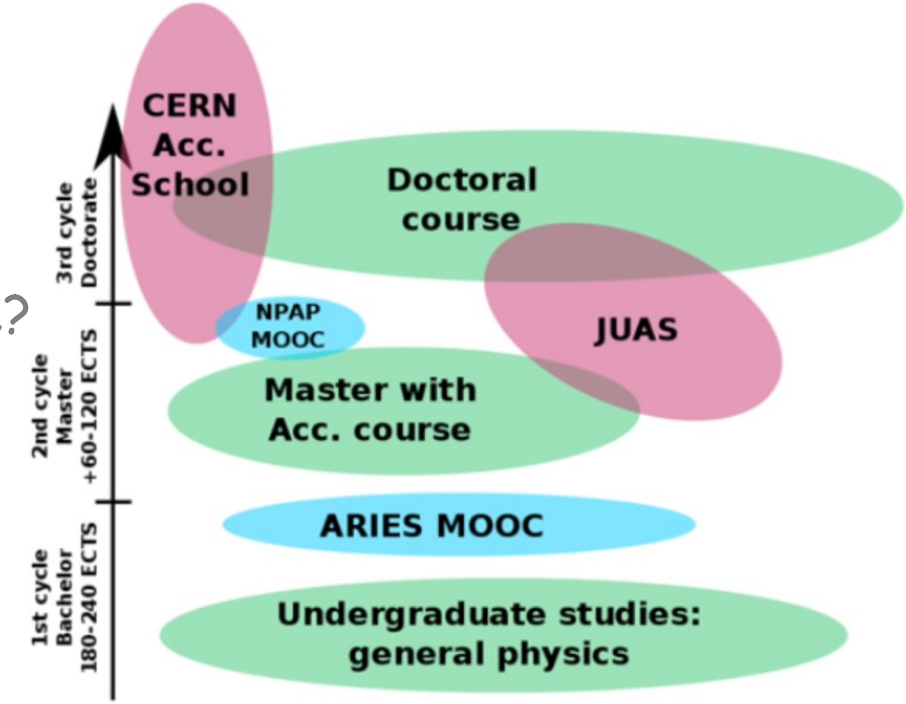
Accelerating News

New Pedagogical tools for Accelerator science?

➢School levels are typically advanced

➢Domains/Field complementarity; User communities

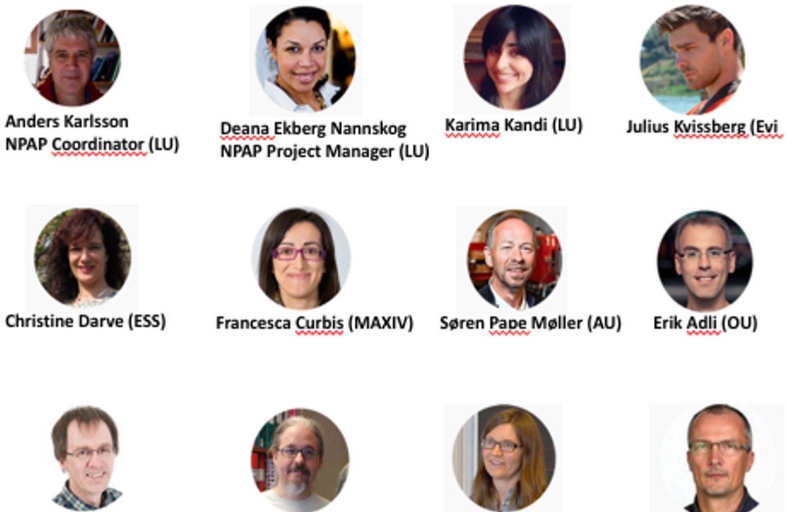
➢To provide sustainable and "users-friendly" tools



Nordic Particle Accelerator Project (NPAP)

From proof of Concept 2015 summer School to MOOC

- Three Summer Schools
- 90 students
- Education in accelerator technology
- Visit of MAXIV and ESS

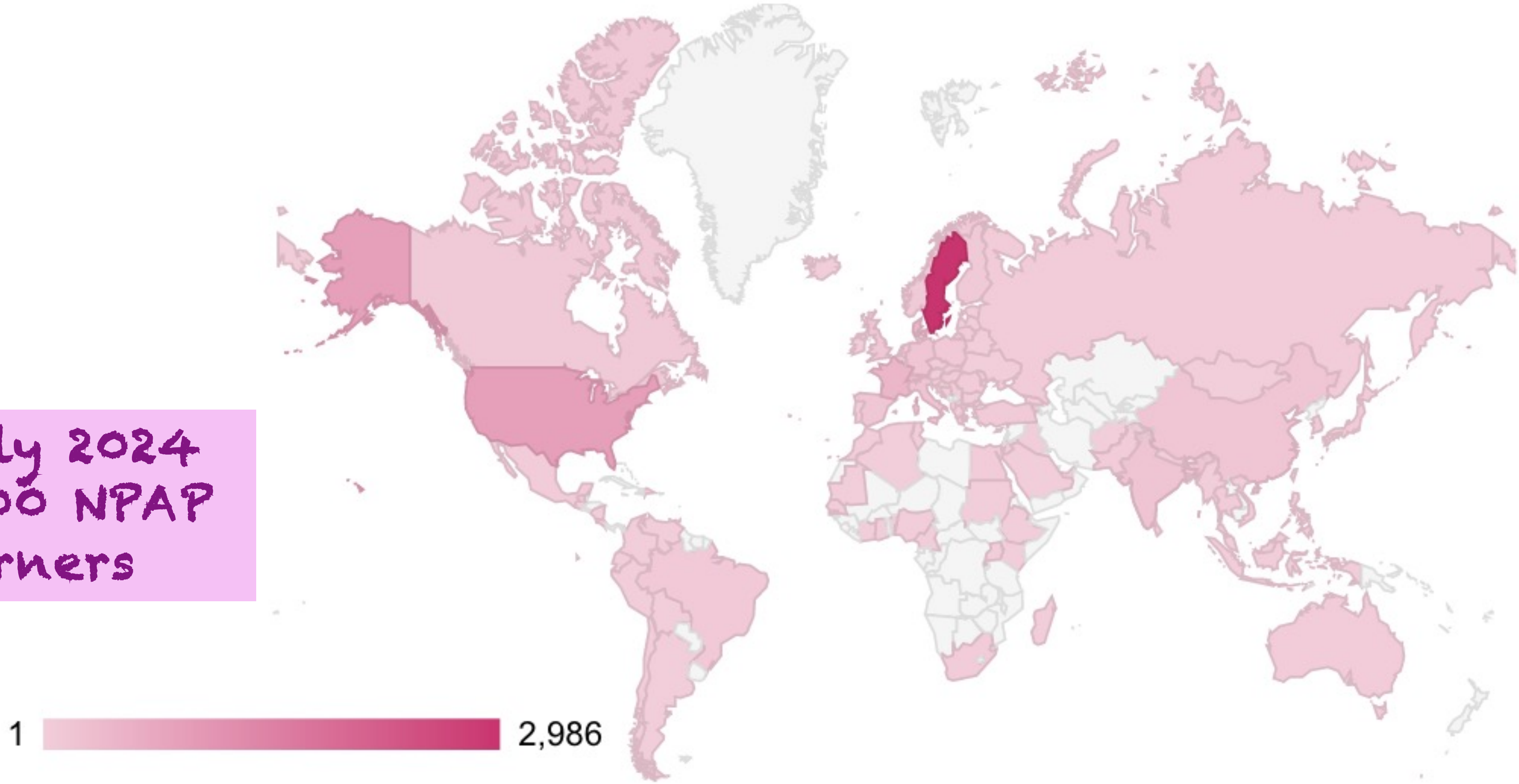


Develop capacity in Northern Europe with emphasize on MAXIV and ESS

Nordic Particle Accelerator Project (NPAP)

We have reached out 104 Countries worldwide !

In July 2024
~ 19,200 NPAP
learners



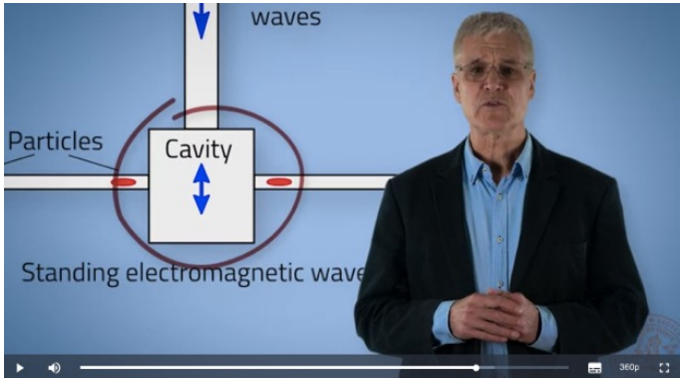
Nordic Particle Accelerator Project - Topics

MOOC1: Particle Accelerators introduction → Launched in August '19	**MOOC2: Fundamentals of accelerator technology** → Launched in March '19	**MOOC3: Medical Applications of Particle Accelerators** → Launched in Nov. '18
Accelerators for Synchrotron Light Light and Light Sources Accelerator to make light The development of accelerators for synchrotron light **Photon light sources and MAXIV** Synchrotron radiation Bending magnets, wigglers and undulators Free Electron Lasers **Spallation source and ESS** Introduction and neutron science European Spallation Source **Particles Colliders** Introduction to Particles Colliders The LHC and its experiments Linear Colliders Future Circular Colliders **Plasma Wakefield** **(to be completed)**	**RF-System** Introduction to RF-systems RF cavities Waveguides RF Amplifiers More about cavities **Magnets technology for accelerators** Magnets part1/2/3 **Beam Diagnostics** An overview Beam intensity and position Transverse Beam Profile Longitudinal Beam Profile Beam Loss Monitoring **Basics of Vacuum techniques** An overview and motivation Residual gases and vacuum regions Vacuum equipment Other vacuum components	**Introduction to the course and radiotherapy** Introduction Biological rational for radiotherapy Intro. to the electron linac for radiation therapy **Electron Linacs for radiation therapy** The multi-energy electron Linac structure Dose delivery to the patient **Proton therapy 1** Rationale of proton therapy Accelerators for proton therapy Treatment delivery of proton therapy **Proton therapy II and production of medical radionuclides** Heavy ion therapy Challenges in pr. th. and heavy ion th. Introduction to medical radionuclides Production of medical radionuclides

NPAP – MOOC Content

MOOC1: Fundamentals of accelerator technology

https://www.coursera.org/learn/fundamentals-particle-accelerator-technology



About this Course

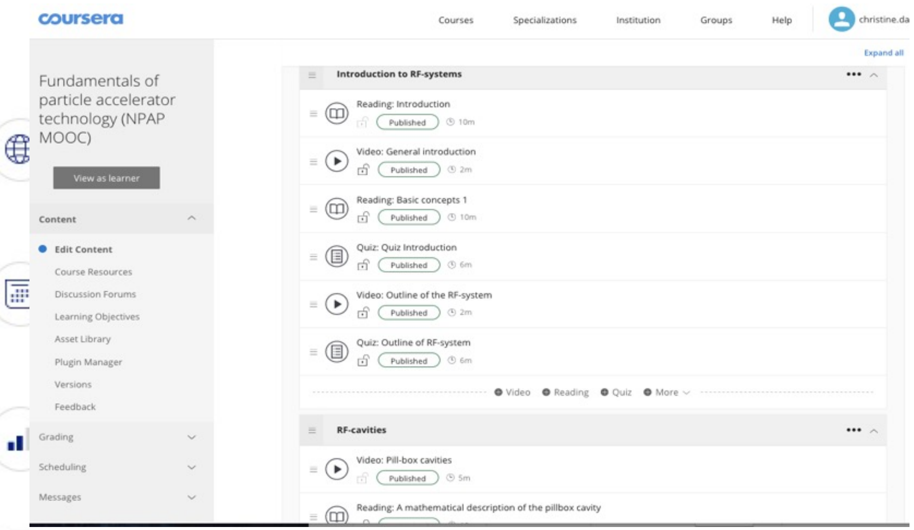
5,694 recent views

Did you know that particle accelerators play an important role in many functions of todays society and that there are over 30 000 accelerators in operation worldwide? A few examples are accelerators for radiotherapy which are the largest application of accelerators, altogether with more than 11000 accelerators worldwide. These accelerators range from very compact electron linear accelerators with a length of only about 1 m to large

SHOW ALL

WHAT YOU WILL LEARN

- ✓ You will learn the basic technology of particle accelerators.
- ✓ You will understand the basic principles for how particles are accelerated, and how they can be guided.
- ✓ You will learn about different ways to monitor the beam.
- ✓ You will learn about vacuum: Why we need vacuum in accelerators; Where particles that give rise to pressure comes from; How one create vacuum



Approx. 17 hours to complete

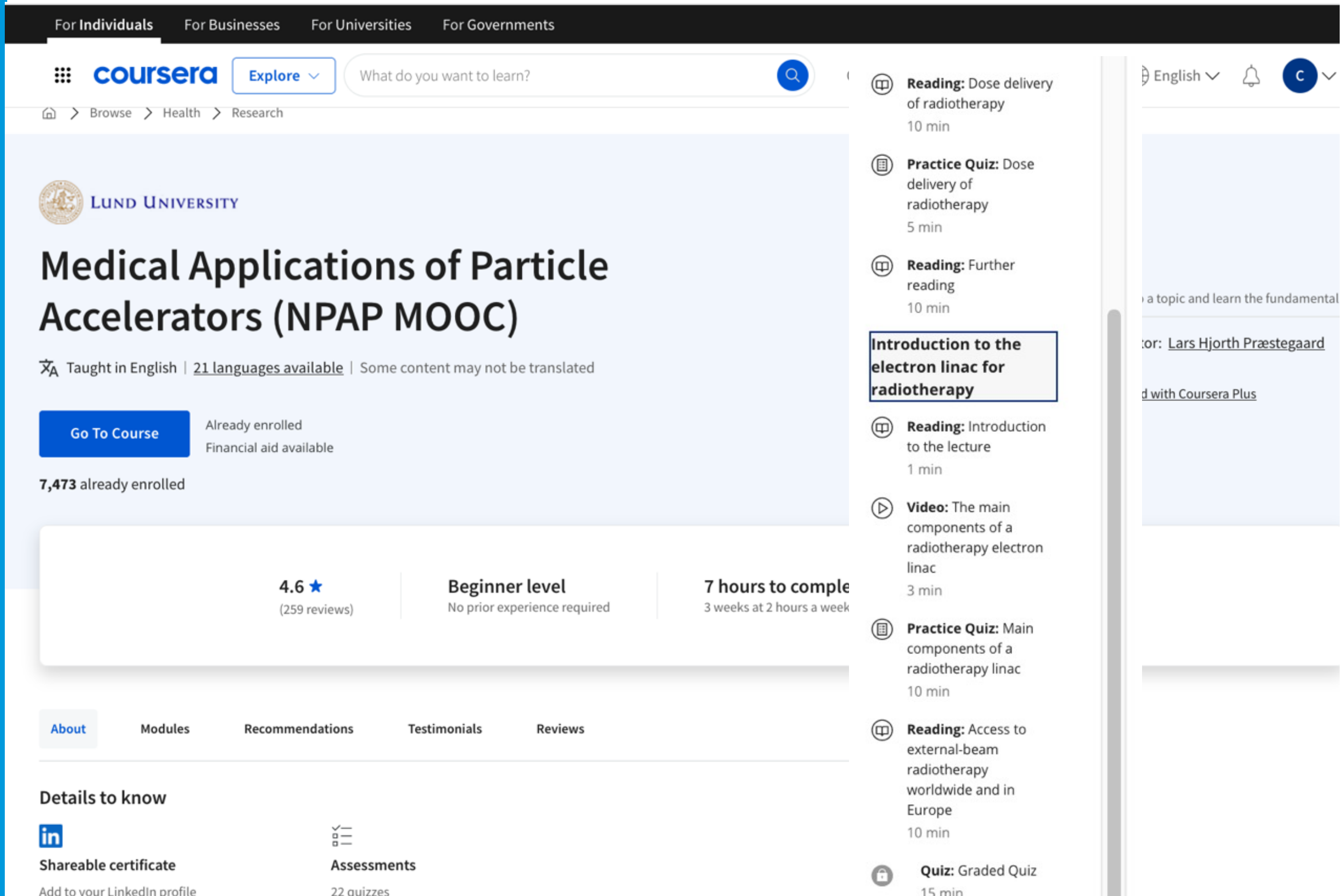
Suggested: 4 weeks of study with 5-8 hours/week

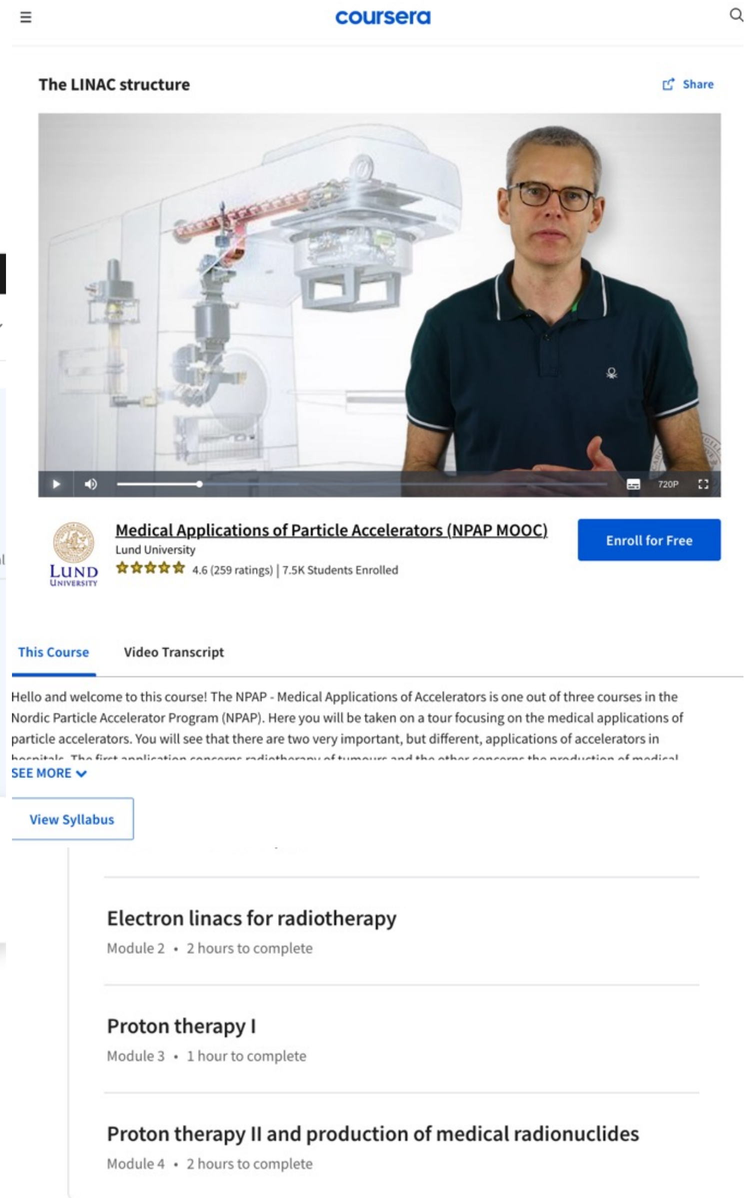
English

Subtitles: English

NPAP - MOOC Content

MOOC3: Medical Applications





NPAP – MOOC Content

Learning Objectives

Week 1: Introduction to the course and Radiotherapy
•Explain the basic principles of radiotherapy
•Give examples of different methods to position the patient before radiotherapy.
•Explain the basic physics of the treatment machines used for radiotherapy

Week 2: Electron linacs for Radiotherapy
•Compare different types of linear accelerators used for radio therapy
•Explain the different systems used to shape the dose distribution in the patient
•Describe how one can radiate a certain volume without damaging the surrounding tissue

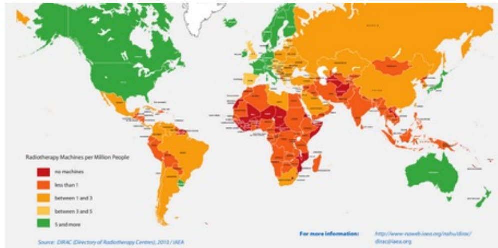


Figure 1: Radiotherapy machines per million people worldwide. Image courtesy IAEA

Overview of the availability of radiotherapy equipment by IAEA: https://dirac.iaea.org/

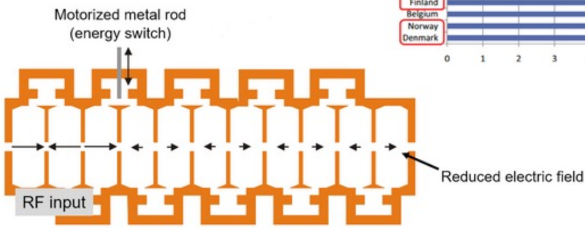


Figure 2: Bi-periodic pi/2 mode linac structure with an energy switch

Figure 3: Varian Clinac energy switch. Image courtesy Varian Medical Systems Inc.

Figure 1: External-beam radiotherapy using an electron linac. Image courtesy Varian Medical Systems, Inc.

NPAP – MOOC Content

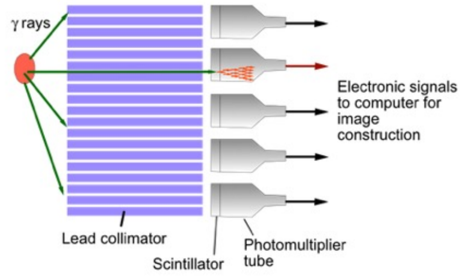


Figure 1: The main components of a gamma camera

	Cyclotron	Synchrocyclotron	Synchrotron
Magnetic field	Fixed	Fixed	Vary
Energy	Fixed	Fixed	Vary
Particle radius	Vary	Vary	Fixed
RF frequency	Fixed	Vary	Vary
Focusing/beam size	Strong/Small	Weak/Large	Strong/Small
Size	Compact	Very compact	Large
Beam pattern	Continuous beam	Pulsed	Pulsed
Avg. beam current	High	Low	Low

Table 1: Main properties of accelerators for proton therapy. The green color indicates properties which are valuable to proton therapy

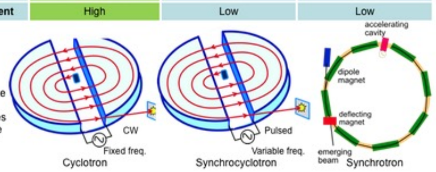


Table 1: Main properties of accelerators for proton therapy. The green color indicates properties which are valuable to proton therapy

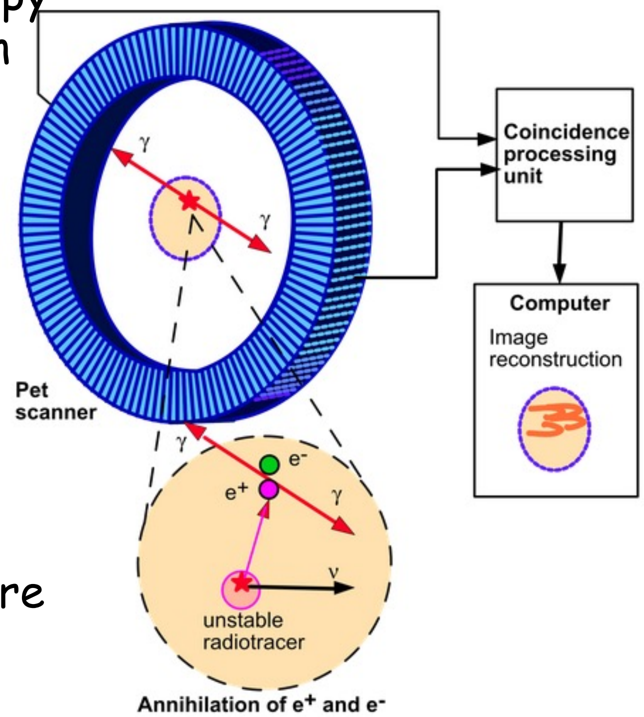
Learning Objectives

Week 3: Proton Therapy I

- Explain the differences of the dose deposition between radiotherapy and proton therapy
- Review the different types of accelerators used for proton therapy
- Explain how the tissue surrounding a tumour is affected by proton therapy
- Explain how protons are accelerated and guided to the patient in proton therapy

Week 4: Proton Therapy II and Production of radionuclides

- Compare heavy ion therapy and proton therapy
- Explain advantages and disadvantages of heavy-ion therapy with respect to proton and x-ray radiotherapy
- Describe how medical nuclides can be produced
- Explain why medical radionuclides are important and where they are used



MOOC Beginner: Accelerate your Teaching

→ Presentation by Joanna Lewis: google drive

https://bit.ly/AT_MOOC23

.. and learn more for free !

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accelerating teaching

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- **Module 1: Introduction to Accelerate Your Teaching MOOC** +
- **Module 2: The Science Behind Large Research Facilities** +
- **Module 3: Accelerating Society from Home-Based Investigations to Massive Collaborations** –
  - 3.0 Module Introduction
  - 3.1 The Physics of Atoms and Particles
  - 3.2 What's the Smallest Thing in the Universe
  - 3.3 Accelerators as Colliders
  - 3.4 AcceleratAR to Study Radiation

Set a weekly learning goal

Setting a goal motivates you to finish the course. You can always change it later.

Casual	Regular	Intense
1 day a week	3 days a week	5 days a week

Set a goal reminder

Course Tools

Bookmarks

Updates

Important dates

Wed, Nov 22, 2023

Course ends

This course is archived, which means you can review course content but it is no longer active.

View all course dates

[Trailers](#)

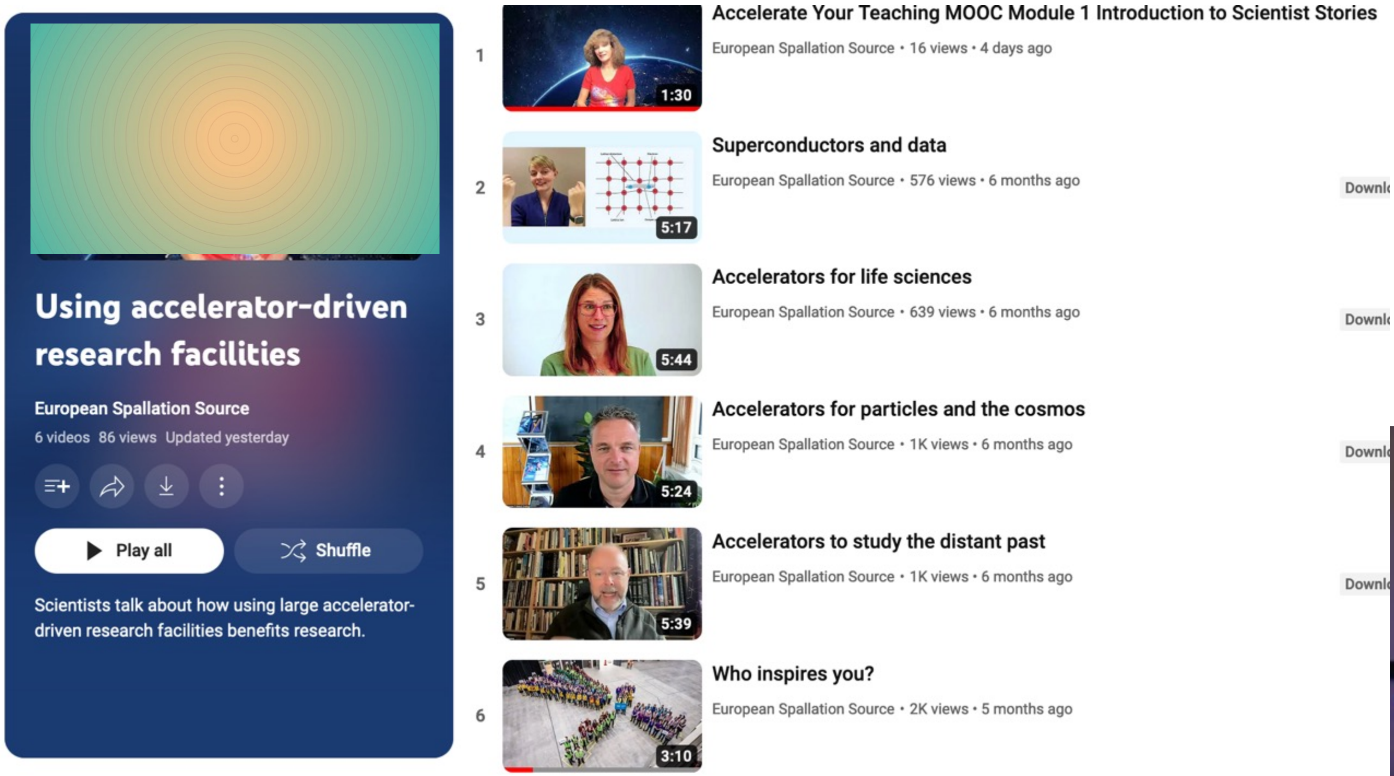
[Descriptions](#)

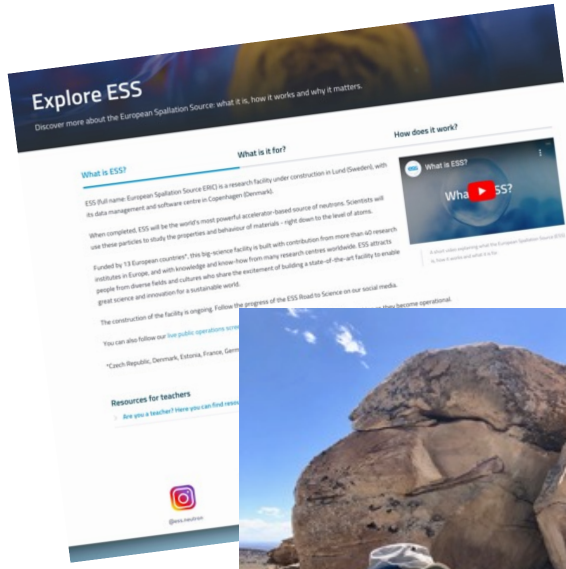
MOOC

accelerating teaching

[Short Videos of scientists](#)

[ess.eu/explore](#)





Science in School

Science in School
The European journal for science teachers

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Science in School > All Issues > Issue 67 >

INSPIRE ARTICLE

Accelerate your teaching with links to cutting-edge science

April 4, 2024
ISSUE 67

Ages: 11-14, 14-16, 16-19

Topics: Biology, Chemistry, Earth science, Engineering, General science, Health, Physics, Resources, Science and society

Keywords: Accelerators, Multidisciplinary science, Particle physics, Teaching resources

Available languages

English

See all articles in English

Author(s): Jo Lewis

Accelerate Your Teaching is a free online course for high-school teachers. Discover how particle accelerator stories can bring a range of STEM topics to life.

Introduction

©Accelerating Teaching

Science in School
The European journal for science teachers

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TEACH ARTICLE

Build a linear accelerator model

April 4, 2024
ISSUE 67

Ages: 14-16, 16-19

Topics: Engineering, Physics

Keywords: Acceleration, Collisions, Energy, Kinetic energy, Magnetism, Momentum

Available languages

English

See all articles in English

Author(s): Jo Lewis, Lukasz Michalak

Build a linear accelerator to demonstrate spallation – the source of high-energy neutrons used by the new European Spallation Source being built in Sweden.

© Ulla Hammarlund/ESS

Supporting materials

Activity instructions sheet

Activity worksheet

ESS scheme

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https://www.eiroforum.org/

Accelerating particles

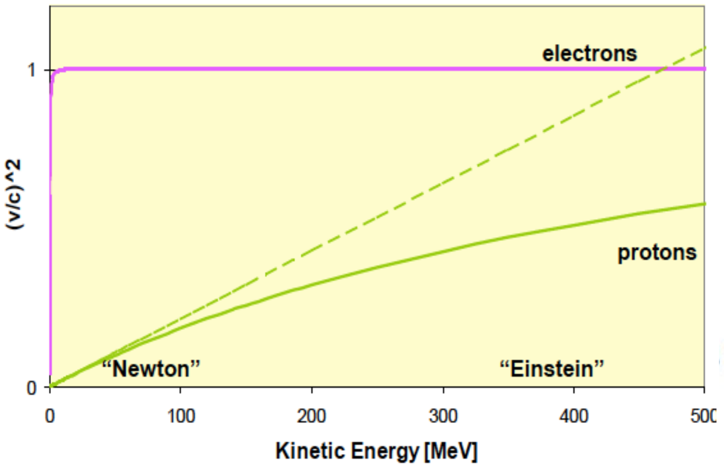
Gang Wang 3 lectures at ASP2021

Electro-Magnetism – Lorentz and Maxwell

$$\vec{F} = \frac{d\vec{p}}{dt} = e(\vec{E} + v \times \vec{B})$$

$$\vec{E} = \underbrace{-\vec{\nabla}\varphi}_{\text{DC}} - \underbrace{\frac{\partial \vec{A}}{\partial t}}_{\text{AC}}$$

	Electron	Proton
Rest mass [Kg]	9.11E-31	1.67E-27
Rest mass [MeV]	0.511	938
V~0.95 c [MeV]	1.1	2000
ratio	1	1836



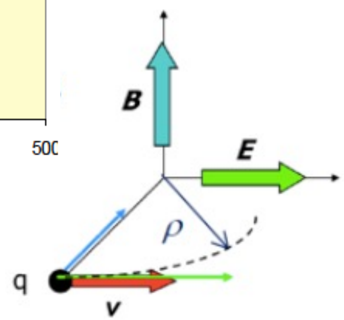
In plane normal to $\vec{B}$:

$$F = evB = \frac{mv^2}{\rho} = \frac{\gamma m_0 v^2}{\rho}$$

$$\frac{p}{e} = B\rho$$

magnetic rigidity

$$B\rho[\text{T.m}] \approx \frac{p[\text{GeV/c}]}{0.3}$$



$$\beta \equiv \frac{v}{c} = \frac{pc}{E}$$

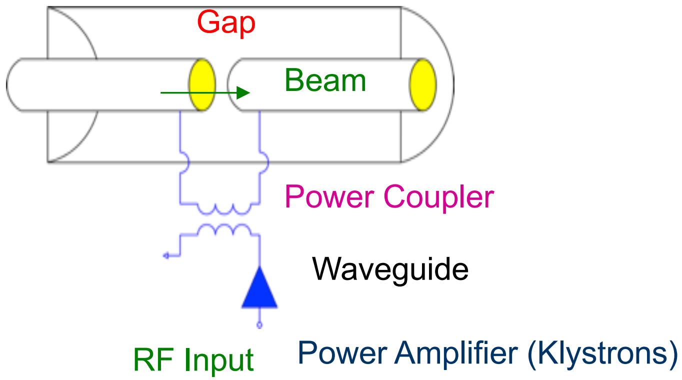
$$\gamma \equiv \frac{1}{\sqrt{1-\beta^2}}$$

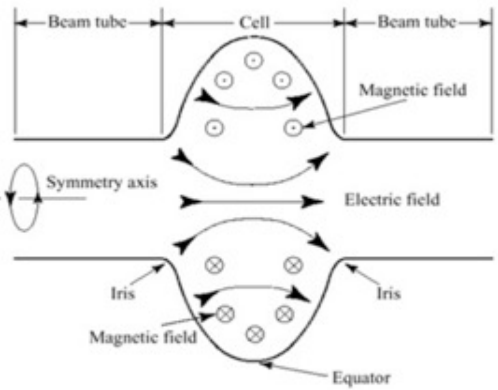
momentum $p = \gamma m v$

total energy $E = \gamma m c^2$

kinetic energy $K = E - mc^2$

$$E^2 = \sqrt{\left(mc^2\right)^2 + \left(pc\right)^2}$$





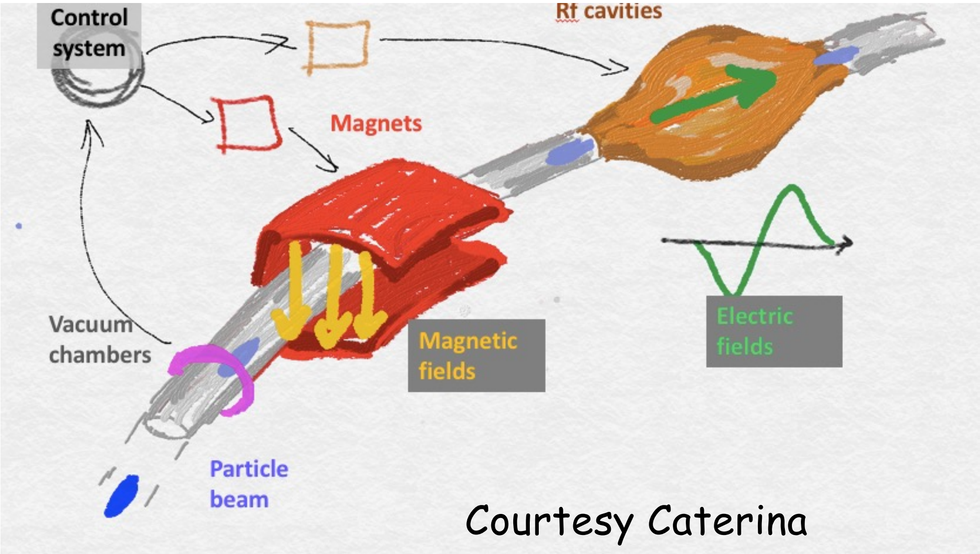
Particle Accelerator Main Ingrédients

1- Ion Source to **produce the charged particles** to be accelerated (h^+ or h^-)

2- Accelerating structures to **accelerate** charged particles → could be SUPRA

3- Magnets are used to **bend and focus** the particle trajectories → could be SUPRA

4- Vacuum chamber to **minimize scattering** of the beam particles by gas particles



Courtesy Caterina Biscari

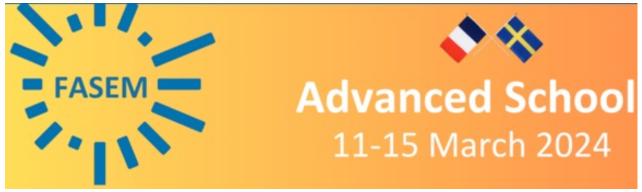
5- Cooling systems to **remove the heat** dissipated in accelerator components; use of superconducting magnet and cavity

6- Beam diagnostics to provide **information** about the **beam** intensity (current), position, beam profile and beam loss

7- Control system to **record and control** each equipment

Applications of Accelerators

FASEM for Life science 2024



"Neutrons for Soft and Biological Matter" by Giovanna Fragneto

French-Swedish Academy for Scattering Experiments and Modeling (FASEM) for Life science: from experiments to data analysis – LINXS Partner Event

Monday, 11 March 2024, 09:00 CET – Friday, 15 March 2024, 17:00 CET

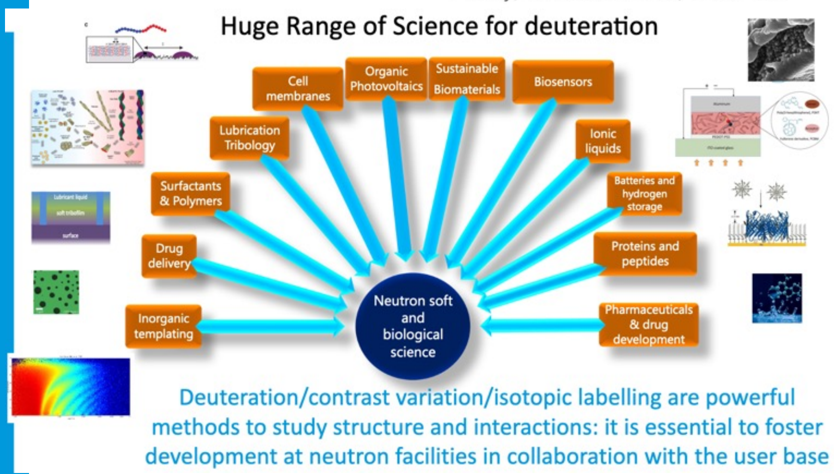
MORE INFORMATION

REGISTRATION AND PROGRAMME IS COMING SOON

When: 11–15 March 2024
Where: at LINXS (Scheelevägen 19, Lund), Workshop room on the 5th floor.

DESCRIPTION

The main objective of this advanced school is **to train young researchers in biology, biophysics, pharmacology, etc. to the use of X-ray (XR) and neutron scattering structural techniques** (crystallography, small-angle scattering, reflectometry), **ranging from experiments to complete and in-depth analysis of the data**, based on mathematical and modeling approaches (*e.g.* analytical fits, *ab initio* modeling, artificial intelligence, Bayesian and multimodal methods). The complementarity of these scattering techniques with other structural biology methods, such as NMR, will be considered as well.



See also: SciLifeLab is a national resource providing unique technologies and expertise to life scientists, fostering cross-disciplinary collaborations among researchers, industry, healthcare, public research organizations, and international partners.

African School of fundamental Physics and applications

A non-profit organization created by a small group of worldwide scientists to stimulate and include more African talented physics students in the world scientific community

The aim of the school is to build capacity in African countries, to harvest, interpret, and exploit the results from physics experiments with particle accelerators, and to increase proficiency in related applications and technologies

- Contribute to a world w/ equal access to knowledge
- Support financially up to 85 African students for 3- week classes attendance
- Establish a biennial educative program to be hosted across Africa
- Provide high quality classes by international re-known Scientists

Details by Mounia Laassiri: ACP2023: An overview of the ASP and Christine&Ketevi "The ASP: Shaping the future", Wits, SA, June '22

African School of fundamental Physics and applications

Particles and related applications

- Nuclear physics,
- Particle physics,
- Medical physics,
- (Particle)astrophysics & cosmology,
- Fluid & plasma physics,
- Complex systems

Light sources and their applications

- Light sources
- Condensed matter & materials physics
- Atomic & molecular physics
- Optics & photonics
- Earth science

Cross-cutting fields

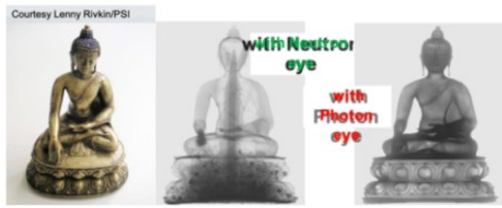
- Accelerator physics
- Computing
- Instrumentation & detectors
- Quantum computing & quantum information
- Machine learning & artificial intelligence

Societal engagement

- Physics education
- Community engagement
- Women in physics
- Early career physicists

ASP online lectures and "Synchrotron and neutron based diffraction and spectroscopic techniques"

Conferences - ACP



Images of Buddha using a Neutron Source and a Light Source

Applications of Accelerators

APS2024 – "Light sources & applications"
by Caterina Biscari (ALBA, ES)

Energy and power emitted in a ring

ALBA

$$P_{SR} = \frac{2cr_e}{3(m_0c^2)^3}\frac{E^4}{\rho^2} = \frac{2r_e c m_0 c^2}{3\rho^2}\gamma^4$$

Larmor formula:
Instantaneous power emitted by an electron travelling in a circle of radius ρ (by integrating the Poynting vector)

$$U_0 = \int_{finite\ \rho} P_{SR}\,dt = \frac{2}{3} r_e m_o c^2 \beta^3 \gamma^4 \oint \frac{ds}{\rho^2} = C_\gamma \frac{E^4(GeV^4)}{\rho(m)} \propto \gamma^4 I_2$$

$$C_\lambda = \frac{4\pi}{3}\frac{r_e}{(mc^2)^3} = 8.846 \cdot 10^{-5} \frac{m}{GeV^3} \quad for\ e^-, e^+$$

Energy emitted per turn by every particle. Note the strong dependence on γ

Emitted power per turn by N_{tot} electrons (positrons) and protons (antiprotons)

$$P_e(kW) = \frac{e\gamma^4}{3\varepsilon_0\rho} I_b = 88.46 \frac{E(GeV)^4 I(A)}{\rho(m)}$$

$$P_p(kW) = \frac{e\gamma^4}{3\varepsilon_0\rho} I_b = 6.03 \frac{E(TeV)^4 I(A)}{\rho(m)}$$

$$I_2 = \oint \frac{ds}{\rho^2}$$

$$r_e = \frac{e^2}{4\pi\varepsilon_o m_o c^2}$$

$$N_{tot} = \frac{I \cdot T_o}{e}$$

15 July 2024 - ASP24

$$P_{SR} \propto \frac{\gamma^4}{\rho^2}$$

$$U_o \propto \frac{\gamma^4}{\rho}$$

$$P_e(kW) = 88.5 \frac{E(GeV)^4 I(A)}{\rho(m)}$$

$$P_p(kW) = 6.0 \frac{E(TeV)^4 I(A)}{\rho(m)}$$

Emitted power per turn by electrons (positrons) and protons (antiprotons)

Electrons are the particles used for synchrotron light production

Applications of Accelerators

"Radionuclide production and radiation therapy with particle accelerators"
by Marco Silari (Polytechnic Milano, IT)

Particle accelerators operational in the world

POLITECNICO MILANO 1863
DIPARTIMENTO DI ENERGIA

Three main applications: 1) Scientific research, 2) Medical applications 3) Industrial uses

Accelerators	1968 [1]	1970 [2]	1989 [3]	1994 [4, 5]	1998 [6–8]	2000 [9, 10]	2004 [11, 12]	2007 [13, 14]	2009 [15, 16]	2012 [17, 18]	2014 forecast
Industrial accelerators,	~2000	~2700	>4000	>4500	~7500	~8500	>8500	~17 900	22 500	25 300	27 000
including											
Electron accelerators rated to energies in excess of 300 keV			~650	1500	1500	1500	>1500	2700	2750	~5000	~5000
Electron accelerators rated to energies below 300 keV			>350	>1000				4500	7000	7500	~8000
Ion implanters and accelerators for ion analysis			~3000	>2000	~6000	~7000	>7000	~9700	~10 000	~11 300	~12 000
Neutron generators								~1000	~2000	~2000	~2000
Accelerators in science				~1000	~1200	~1200	~1200	~1200	~1200	~1200	~1200
Accelerators in medcine,		306	>2500	~4200	~4700	~5200	~8500	~9650	~11 600	~13 000	~14 000
including											
Electron accelerators			~2500	~4000	~4500	~5000	~7500	~9000	>11 000	~12 000	~13 000
Proton and ion accelerators (radiotherapy) [19]			11	17	20	20	25	29	32	39	~59
Production of radioisotopes for medicine				~200	~200	~200	~260	>550	>600	~1000	~1100
Total	~2000	~3000	>6500	>9700	>13 500	>15 000	>18 000	~27 500	~30 000	~39 500	41 000

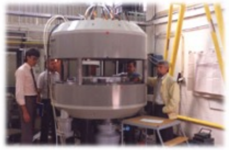
A. P. Chernyaev and S. M. Varzar, Particle Accelerators in Modern World, Physics of Atomic Nuclei, 2014, Vol. 77, No. 10, pp. 1203–1215.

M. Silari –RN Production and RT with particle accelerators – ASP 2024 9

Particle accelerators for medical uses

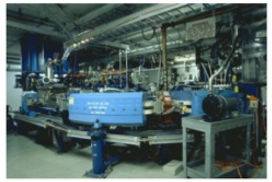
POLITECNICO MILANO 1863
DIPARTIMENTO DI ENERGIA

I. Production of radionuclides with (low-energy) cyclotrons
   i. Imaging (PET and SPECT)
   ii. Therapy



II. Electron linacs for conventional radiation therapy (including advanced modalities)

III. Medium-energy cyclotrons and synchrotrons for hadron therapy with protons (250 MeV) or light ion beams (400 MeV/u ^{12}C-ions)

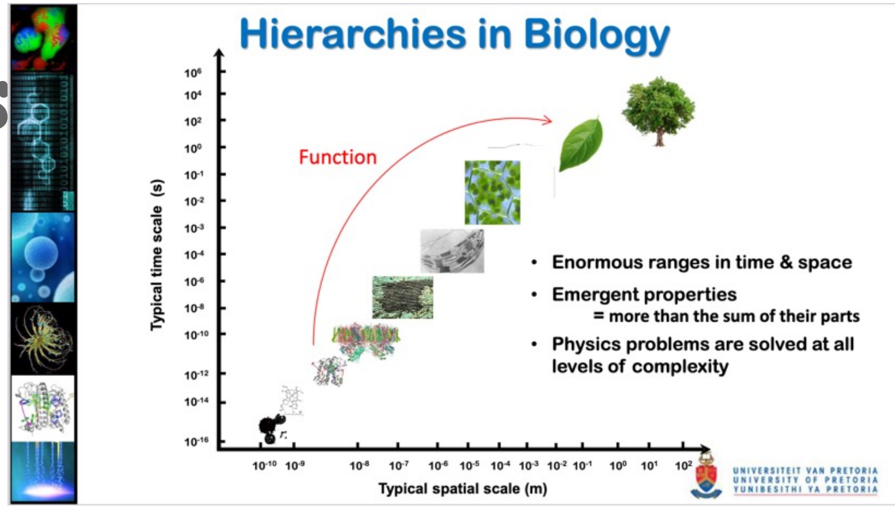


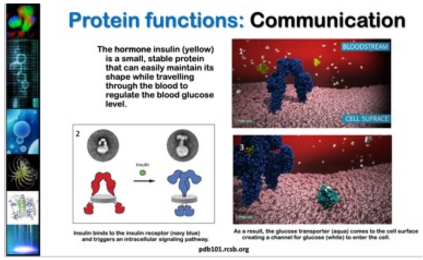
IV. Compact proton accelerators for BNCT

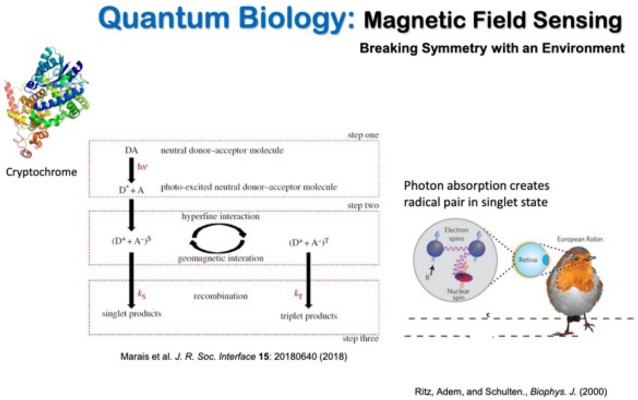
M. Silari –RN Production and RT with particle accelerators – ASP 2024 10

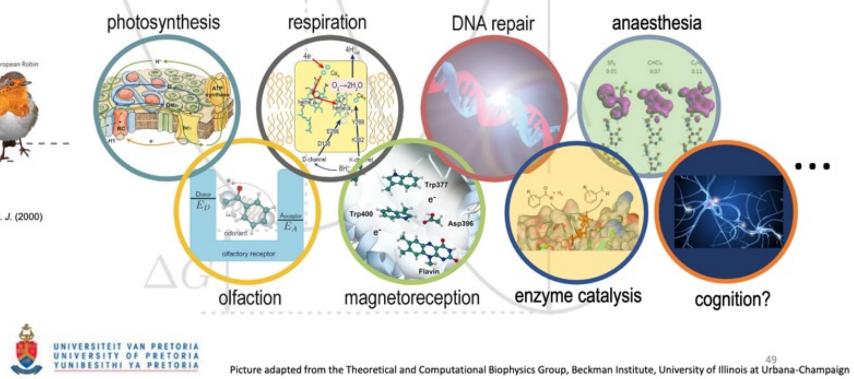
Applications of Accelerators

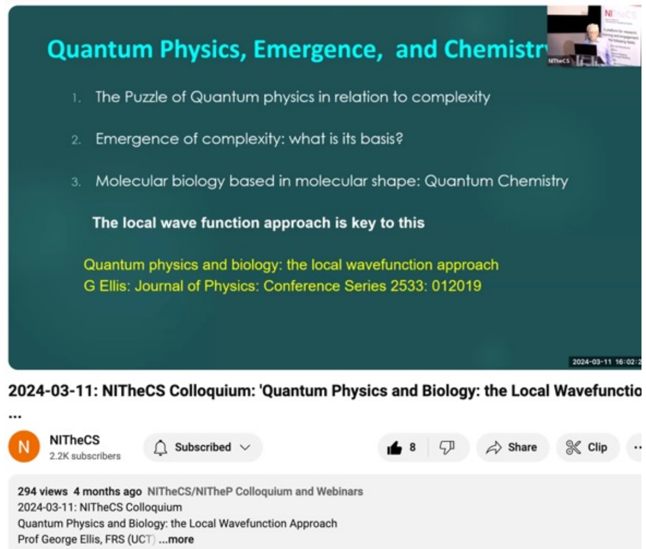
APS2024 – "Fundamentals of Biophysics"
by Tjaart Krüger (Pretoria, SA)











2024-03-11: NITheCS Colloquium: 'Quantum Physics and Biology: the Local Wavefunction "
by George Ellis (UTC, SA)

APS Forum on International Physics FIP

FIP/PHYSICS MATTERS

- SESAME Light Source (members and observers) and Developing Communities
- Matters for Users: Scientific Cases using Photon and Neutron Sources
- Particle Accelerator and large Research Infrastructure
- Outreach & Education
- Organizations & Collaborations
- Forums and Topical colloquia:
  - Environmental & Sustainable developments
  - Health & Life Science

42+1 Colloquia so far!

Gathering up to 34 countries at once

Watch the latest PHYSICS MATTERS edition: "Forum to accelerate a global digital world"

YouTube recordings available

Past PHYSICS MATTERS Colloquia Below

April 2024: "Forum to accelerate a global digital world" by Dr. Christine Darve and Dr. Stephane Kenmoe

Subscribe/unsubscribe form

Next: "TechWomen: Harnessing the power of global women in STEM"
Thursday July 25, 2024 ' 16:00 CET (10:00 ET)

Learn more "Why Physics Matters!"

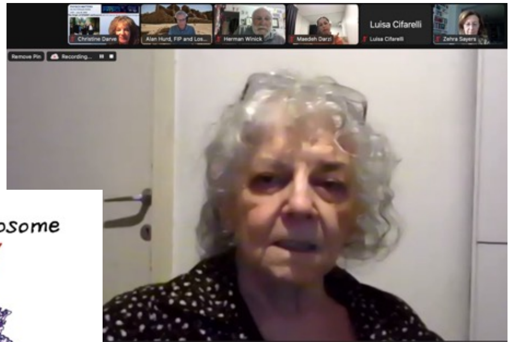
"Facilitating Global Scientific Exchange: The "Impact of PHYSICS MATTERS", e-EPS

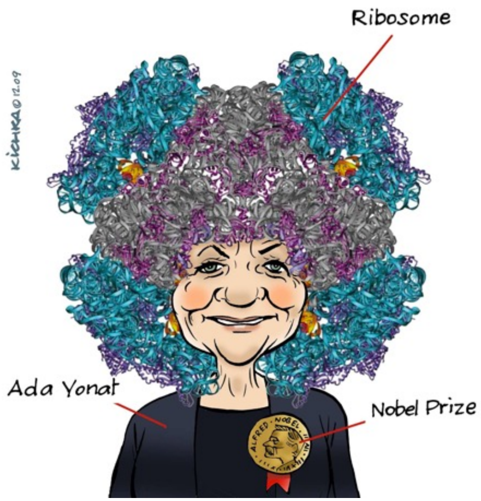
FIP/PHYSICS MATTERS

"[How do intruders take over their hosts?]"

SCIENTIFika, April 2021

Prof. Ada Yonath
2009 Nobel Prize
in Chemistry





Ribosomes and Proteins crystallography

⊖ 🇸🇪May 2024: " Neutron Scattering: Exploring Cell Membrane Mechanisms" by Prof. Giovanna Fragneto

Thursday, May 24, 2024

"Neutron Scattering: Exploring Cell Membrane Mechanisms"

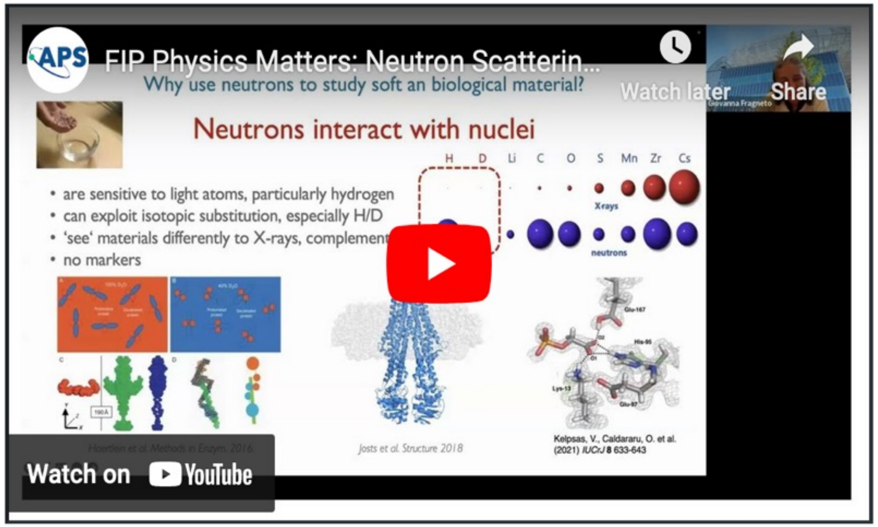
See Slides:

- [Slides_GiovannaFragneto]

For complementary information:

- **See Also: Nobel Laureate Prof. Ada Yonath** explaining "How do intruders take over their hosts?" (SCIENTIFika event organized in collaboration with ESS, MAXIV on the basis of APS March meeting "Chat with the Experts") Prof. Ada Yonath, Israeli crystallographer, received her Nobel Prize in Chemistry in 2009 for her pioneering work on the structure of the ribosome. [PHYSICS MATTERS - July 2021]
- PHYSICS MATTERS Colloquium - Thursday, April 27, 2023- "Role of large-scale facilities for battery research and innovation" by Prof. Aleksandar Matic

Speaker: Prof. Giovanna Fragneto, European Spallation Source (ESS) Science Director



International Union of Pure and Applied Physics WG14

Mandate

Promote the exchange of information and views among the members of the international scientific community in the field of Accelerator Science including, but not limited to, the following:

- Education and training in Accelerator Physics and Technology
- The theory and experiments concerned with the nature and properties of particle accelerators ar beam physics
- The improvement of international communication in Accelerator Science through the sponsorship professional meetings
- The future of accelerator facilities for various fields that benefit science and society
- The industrial, medical, energy production and environmental applications of relevant accelerator technologies

More Accelerator Conferences via IUPAP

More Suggestions

➢ International Atomic Energy Agency (IAEA) (incl. interactive map)

➢ **American Physical Society (APS) selected FIP Sessions** **(2024-25)**

➢ https://lightsources.org/

lightsources.org 20 years

One voice for the brightest science since 2004

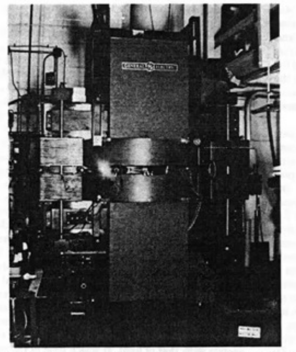


Fig. 1. 70-MeV synchrotron with optical radiation from the electron beam visible through the glass wall of the vacuum "donut" tangent to the beam orbit.

279 Am. J. Phys., Vol. 51, No. 3, March 1983

75 Years of Science with Synchrotron Light

See: next conference (Aug. 26-30) on Synchrotron Radiation Instrumentation (SRI2024)

➢ Central European Research Infrastructure Consortium (C-ERIC):

#Light Source Selfies

Inspired by the light

- Connecting Industrial R&D Staff to State-of-the-Art Neutron Methods
- Cancer Brochure

Platform: CERIC - ACCELERATE

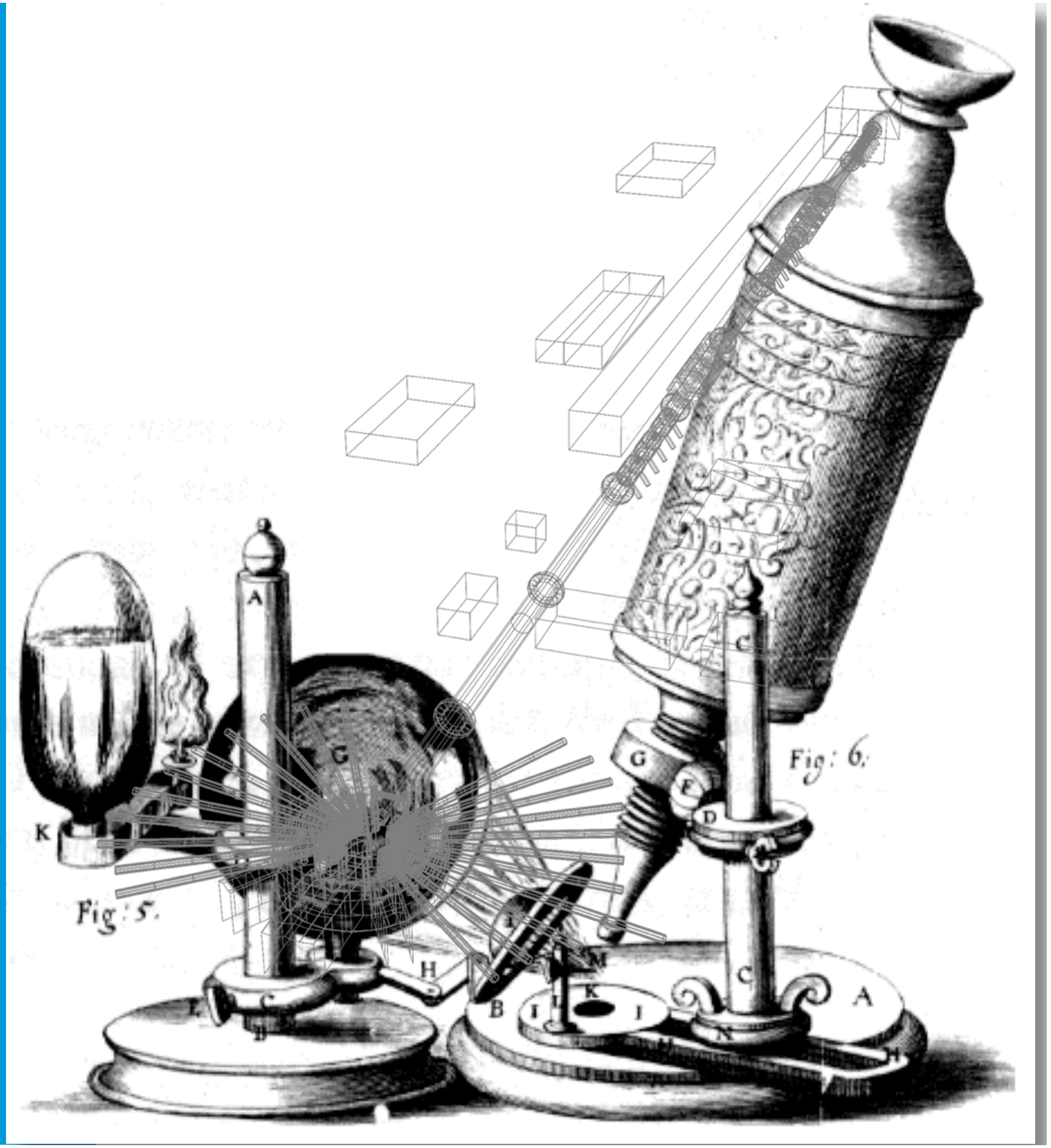
➢ LINXS – Institute of advanced Neutron and X-ray Science

See: Additonal article: "What is the size of the global light- and neutron source research communities?"

➢ National Institute for Theoretical and Computational Sciences (NITheCS)

See: "Engaging in a digital educated world with large scale-projects" Coll. Oct. '23

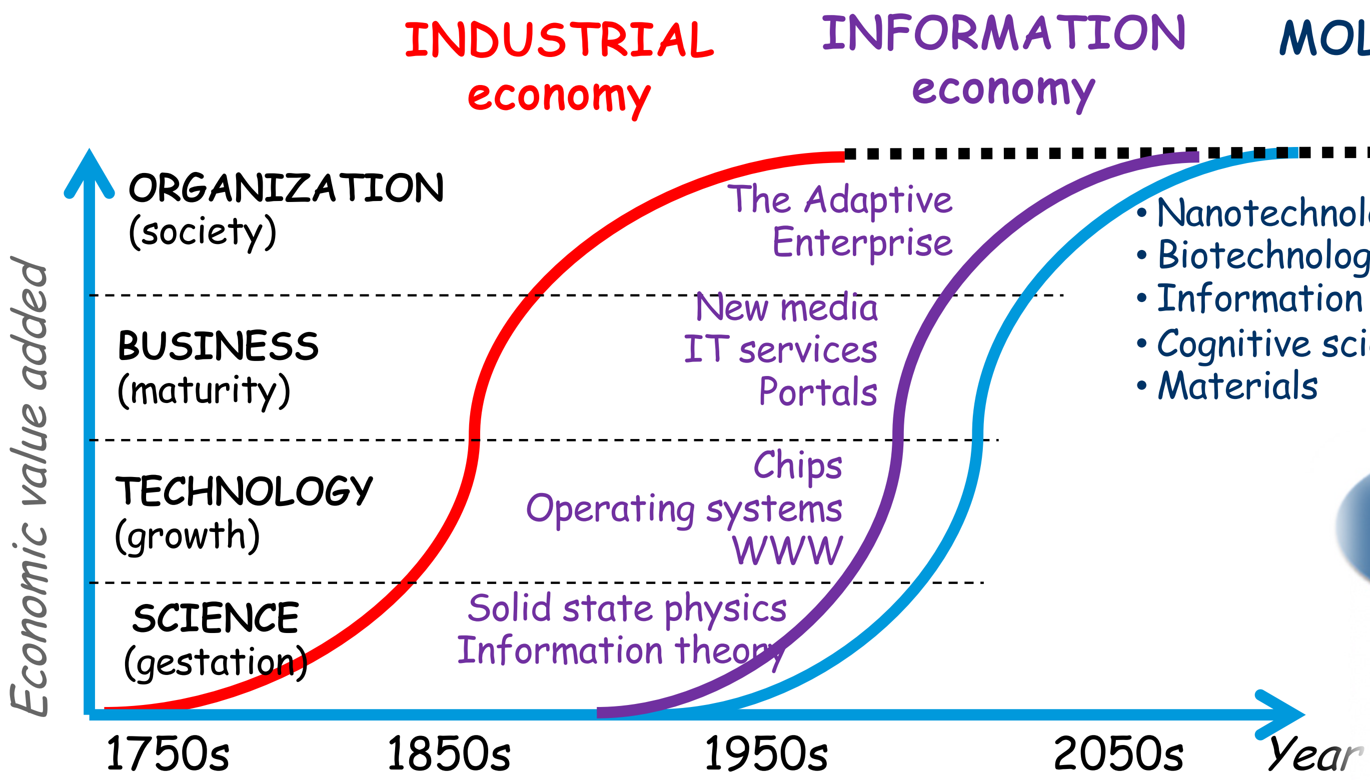
Accelerator for Innovation in Life Science



Sharing for a Sustainable Future

Paradigm for healthcare

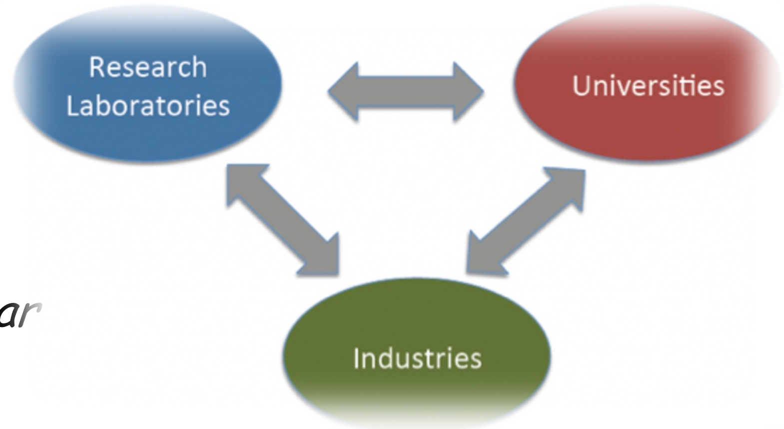
Materials & life science facilities are keys to new economy



- Nanotechnology
- Biotechnology
- Information technology
- Cognitive science
- Materials

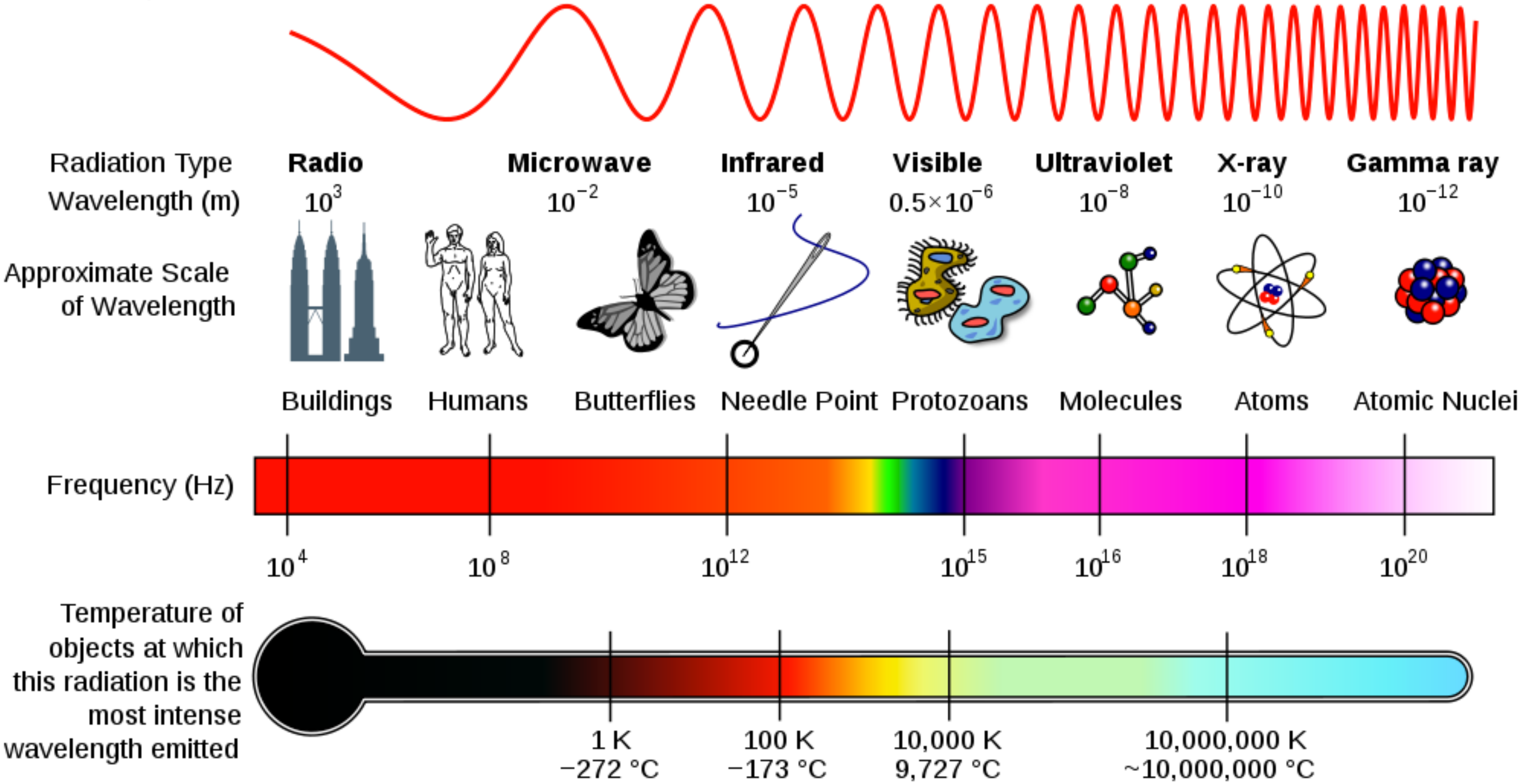
ESS Bilboa – SOCIO-ECONOMIC IMPACT

The Spanish contribution from ESS Bilbao to ESS European Spallation Source ERIC



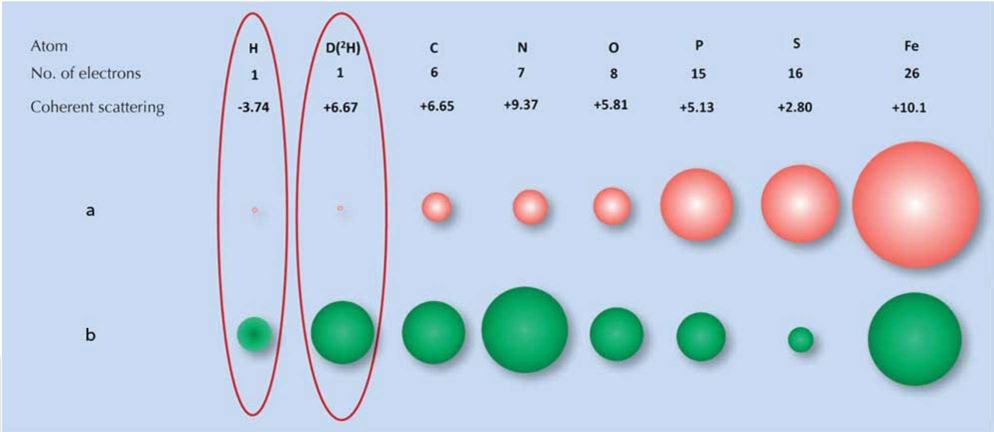
It's Alive - The Coming Convergence of Information, Biology, and Business Christopher Meyer 2003

The ElectroMagnetic Spectrum

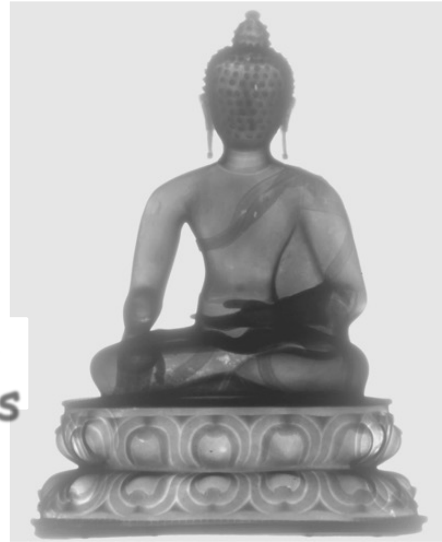


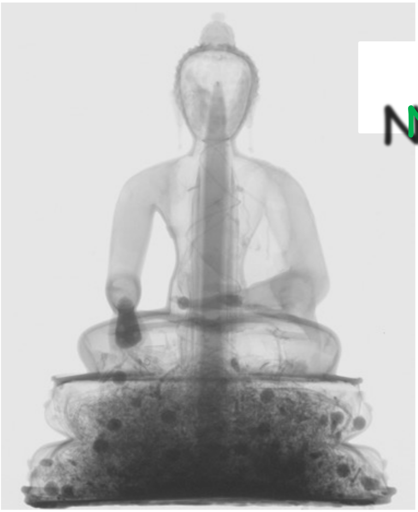
Photons & Neutrons as tools for discovery

Courtesy Lenny Rivkin/PSI

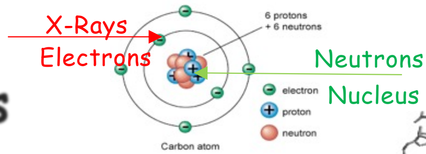


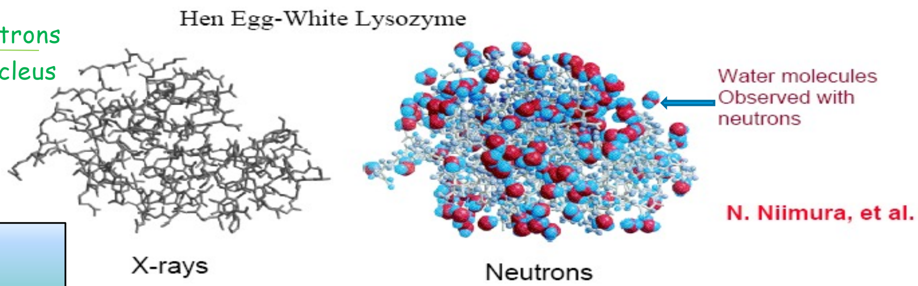
with X-Rays eyes





with Neutrons eyes

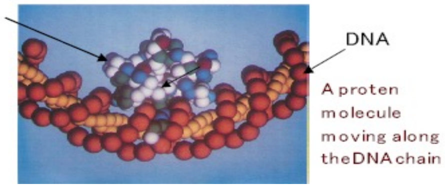




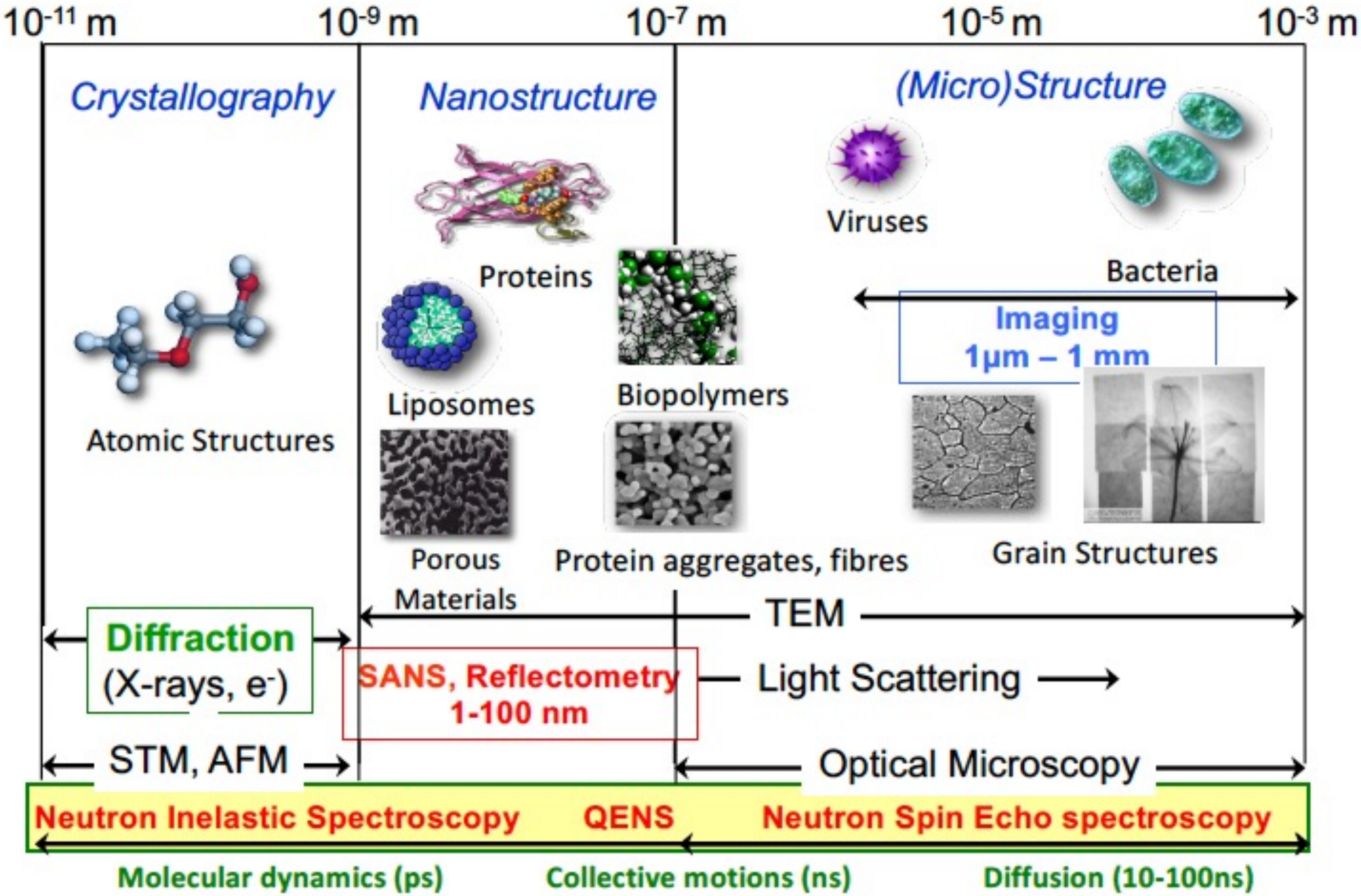
H atoms make up *~50% of atoms of biological macromolecules* (lipids, proteins, nucleic acids, carbohydrates)

Protein

From structure to function

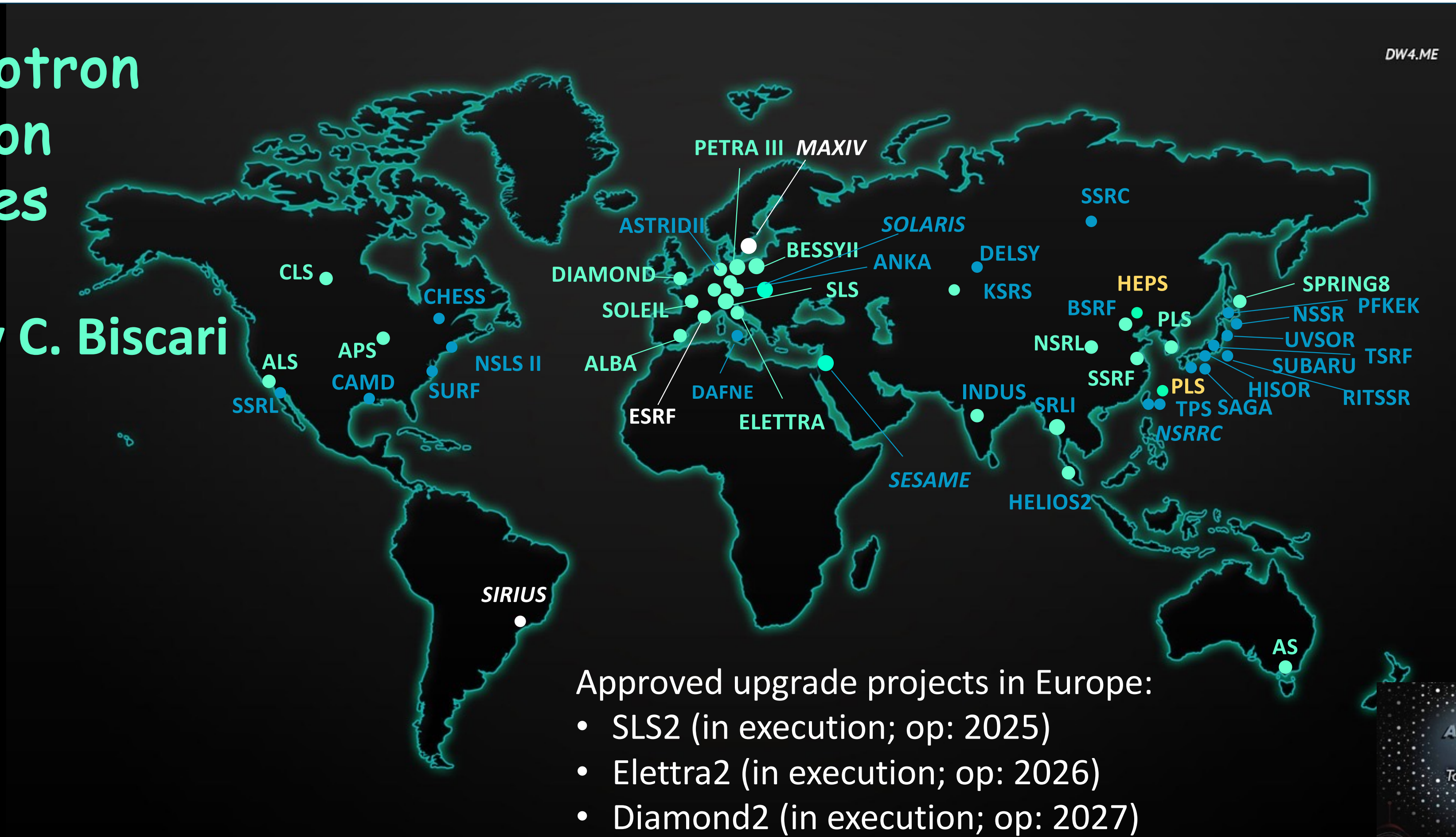


Life science using photons and neutrons as a tool !



Synchrotron Radiation Facilities

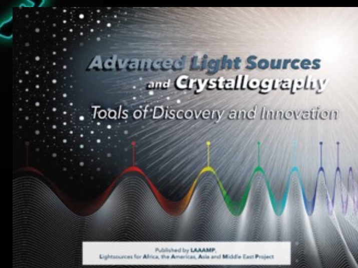
Courtesy C. Biscari



- 4th Generation IN OPERATION
- 4th Generation *in construction*
- Upgrading or planning upgrade from 3rd to 4th generation
- 3rd generation

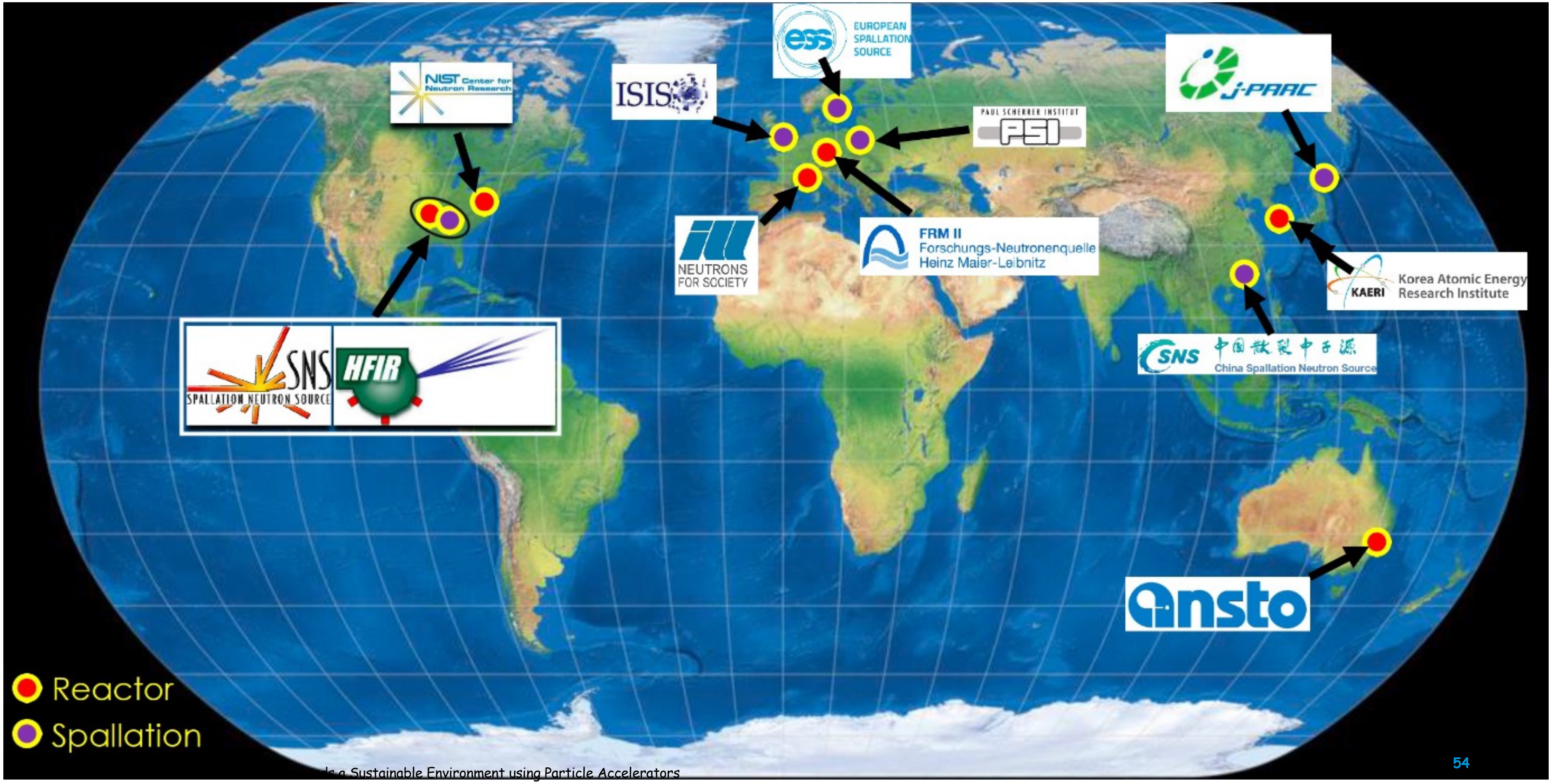
Approved upgrade projects in Europe:

- SLS2 (in execution; op: 2025)
- Elettra2 (in execution; op: 2026)
- Diamond2 (in execution; op: 2027)
- Soleil2 (in execution; op: 2028)



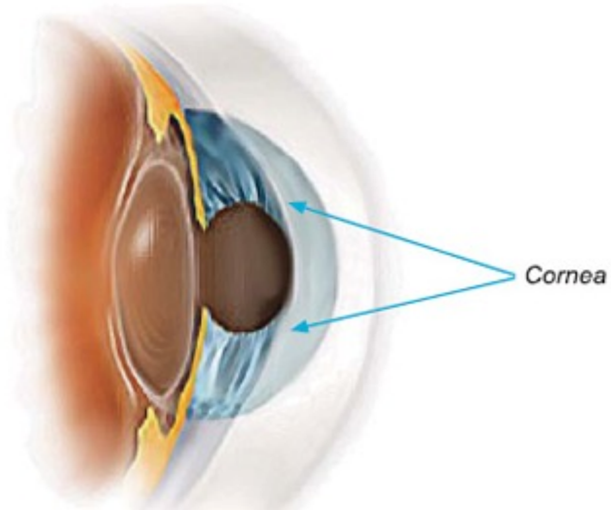
LAAAMP brochure: "*Advanced Light Sources and Crystallography: Tools of Discovery and Innovation*"

Neutron sources around the world



Case: Advanced Materials for Health

Life sciences



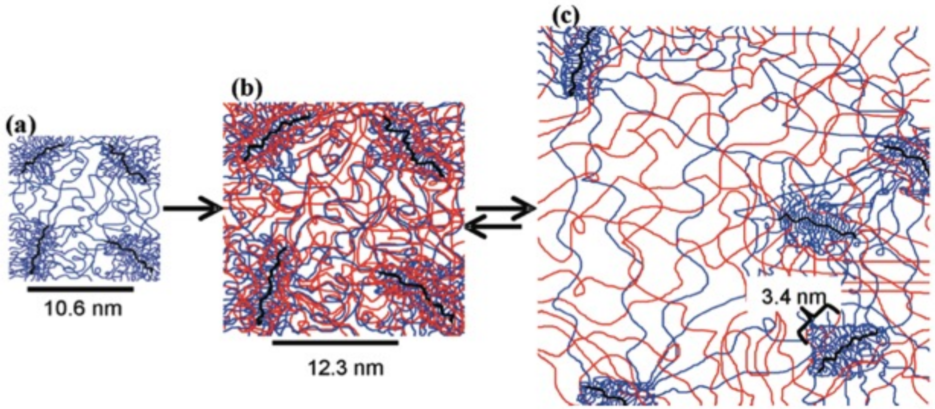
Double network hydrogels provide strength and resilience together with high water content.

Gel structure forms over **multiple length scales.**

Kinetics of gelation can be rapid needing **sub-second** time resolution.

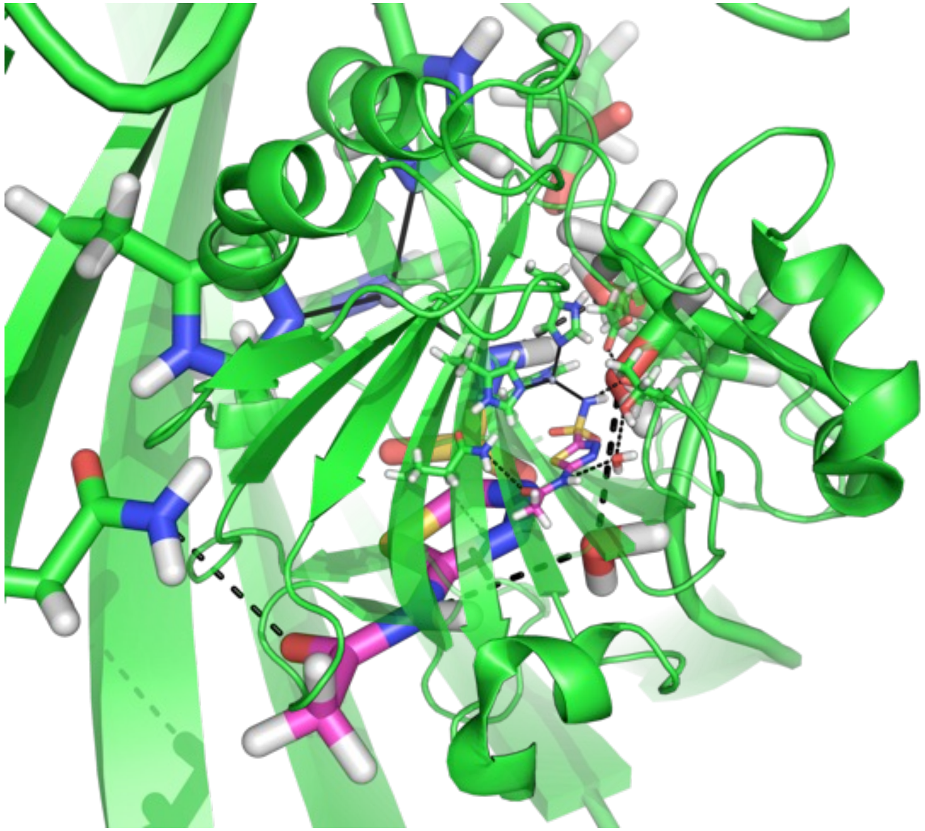
Neutrons provide the structure of each component in the presence of the other.

Swelling of a double network hydrogel designed for use as a cornea replacement.
(Frank Group, Stanford)



Life sciences

Case: Neutrons reveal how drugs interact with drug targets



Carbonic anhydrase

- Enzyme
- Transports CO_2
- Regulates blood acidity

Scientists are studying its role in some cancers, glaucoma, obesity and high blood pressure

Neutron crystallography pinpoints protons and waters in the active site, showing how the drug Acetazolamide binds to this enzyme

Image: Fisher, S. Z. *et al.* 2012 JACS

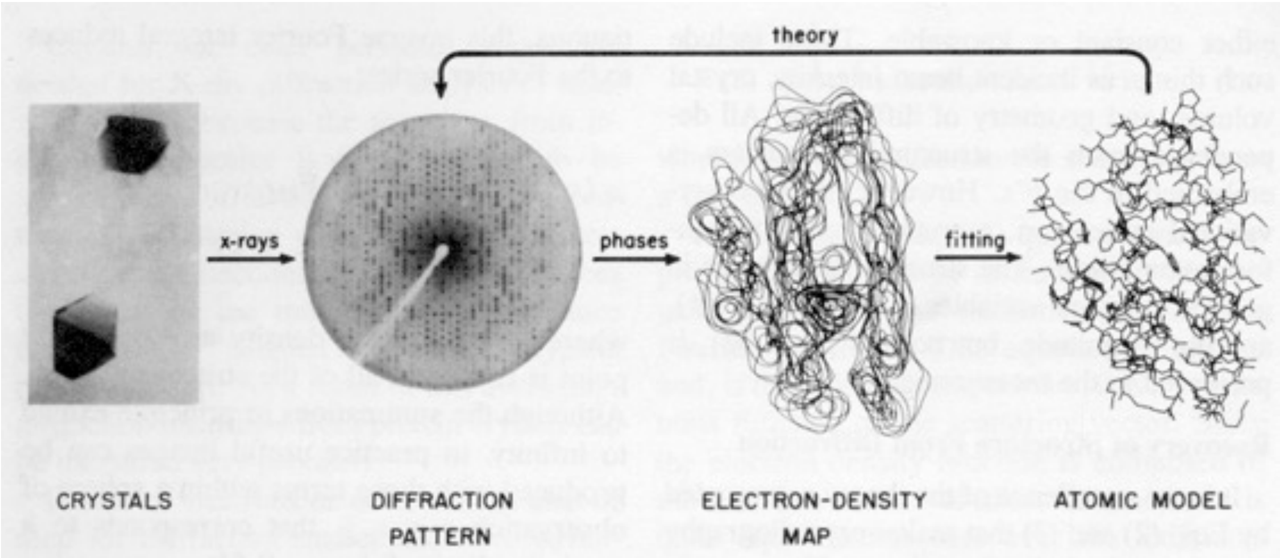
Neutron Protein Crystallography (NPX)

- NPX is used to determine the atomic crystal structure of protein molecules. Uses neutrons in the wavelength range ~ 0.7 to 7 Å
- Single crystal Bragg diffraction (can be monochromatic or Laue) – same as X-ray diffraction theory.
- Data quality is significantly weaker and takes longer to collect. Quality, speed enhanced in *labeled samples*, still requires large crystals.

→NMX Instrument:

See Kalliopi Kanari *"Neutron Sources: Thermal neutron detection at ESS"*

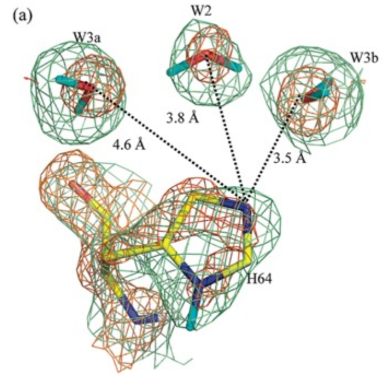
ASP2021



NPX: the ability to "see" Hydrogen atoms

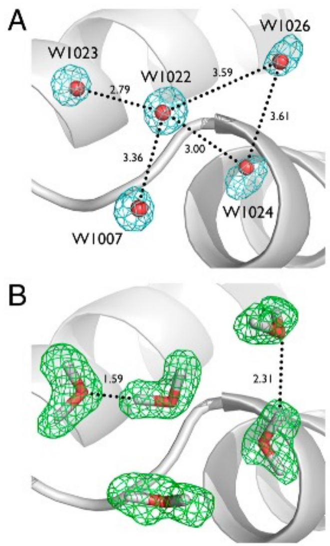
"[Neutron protein crystallography reveals molecular details of inhibitor binding to clinical targets]" by Zoe Fischer

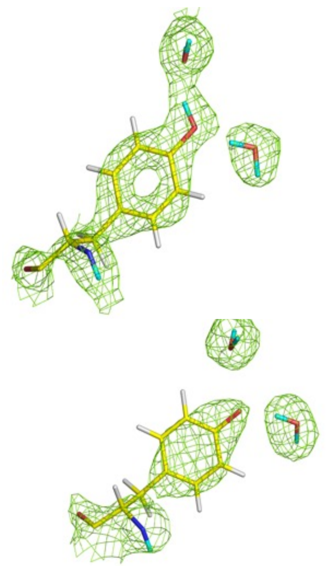
Elucidate enzyme mechanism and function
Protonation states, orientation of amino acid residues
Observe water structures/H-bonded networks
Discerning solvent species (D_2O vs OD^- vs D_3O^+)

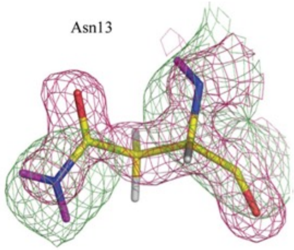


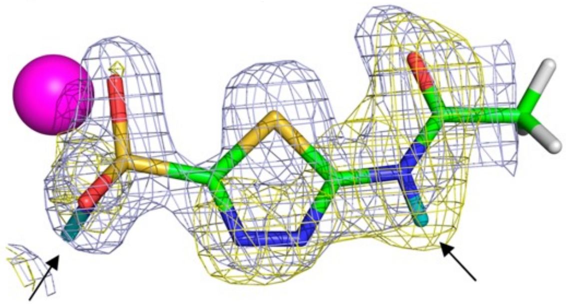
with X-Rays eyes

with Neutrons eyes





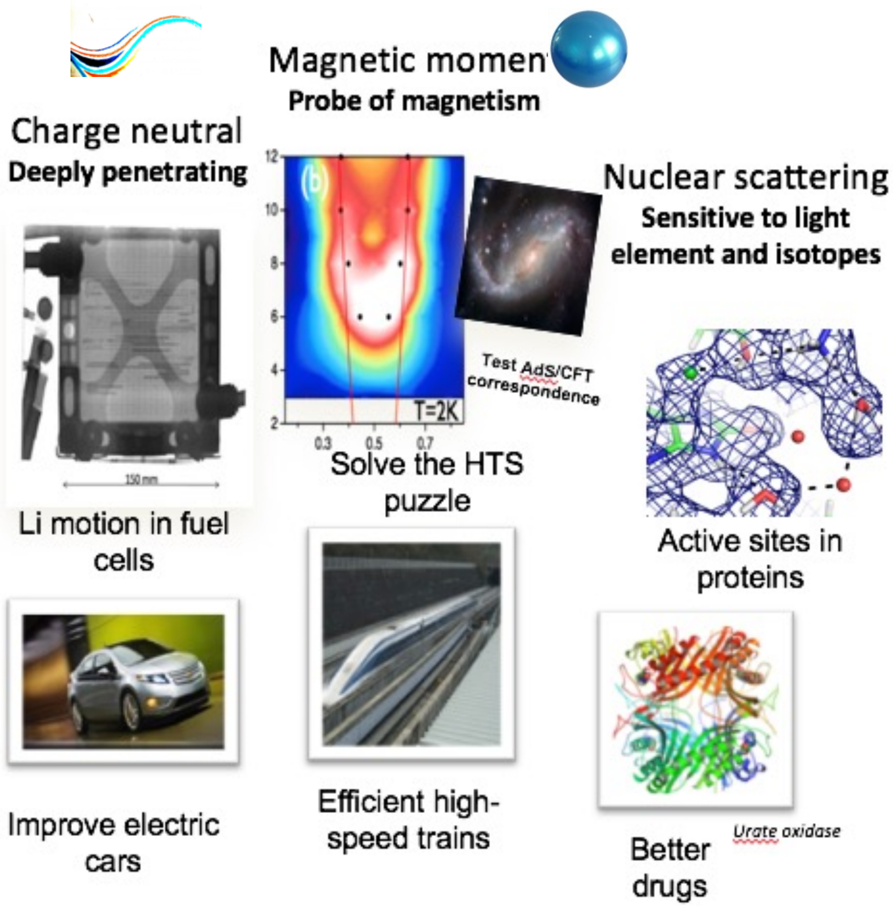


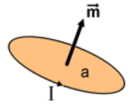


It can also: tell us about H/D exchange kinetics, minimal protein folding domains and solvent accessibility, ***drug/inhibitor/substrate binding interactions.***

Neutrons: all in one …

Wave | **Particle** | **Magnetic moment** | **Neutral**



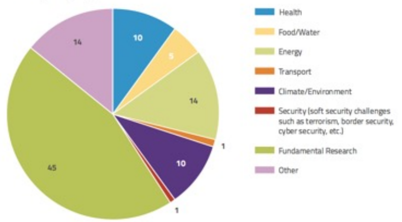


- They have **wavelengths** appropriate to inter-atomic distances
- They have **energies** comparable to molecular motions
- They **interact weakly** with materials, and can penetrate into the bulk
- They are **non-destructive**
- Most important: *they see a completely different* ***contrast*** *compared to x-rays* (with appropriate isotope labelling).

ESS Neutron Instrument for soft/bio science

Andersen, K. H.; Argyriou, D. N.; Jackson, A. J. et al. The Instrument Suite of the European Spallation Source. *Nuclear Instruments and Methods in Physics Research Section A:* **2020**, *957*, 163402. https://doi.org/10.1016/j.nima.2020.163402.

Fig 3.14 Europe: Horizon 2020 topics and challenges expressed as a percentage of research, averaged over all participating neutron sources

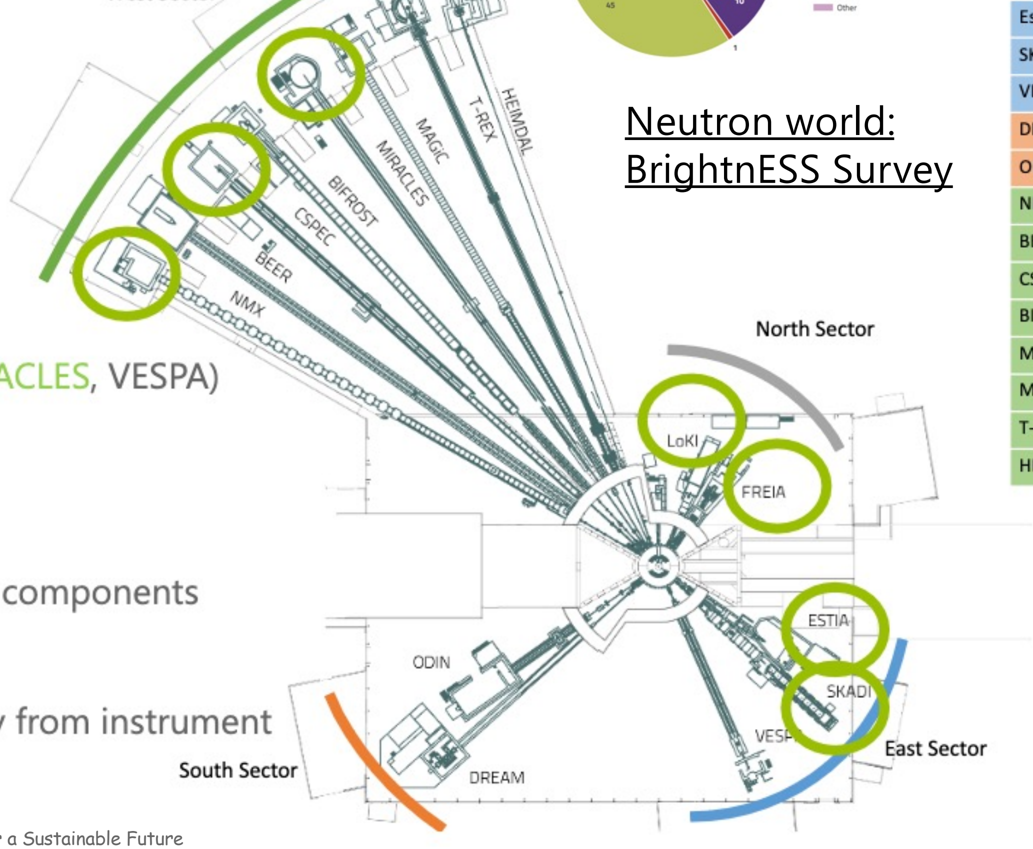


15 instruments + Test Beamline

Diffractometers (DREAM, MAGiC, HEIMDAL)
SANS (LoKI, SKADI)
Reflectometers (Estia, FREIA)
Imaging (ODIN)
Engineering Diffraction (BEER)
Macromolecular Crystallography (NMX)
Spectrometers (CSPEC, T-REX, BIFROST, MIRACLES, VESPA)

Novel detector technologies and geometries
Complex pulse-shaping

Shared neutron bunker – common space for components
Common timing system for facility
Single controls infrastructure (EPICS)
Control and data recording running remotely from instrument

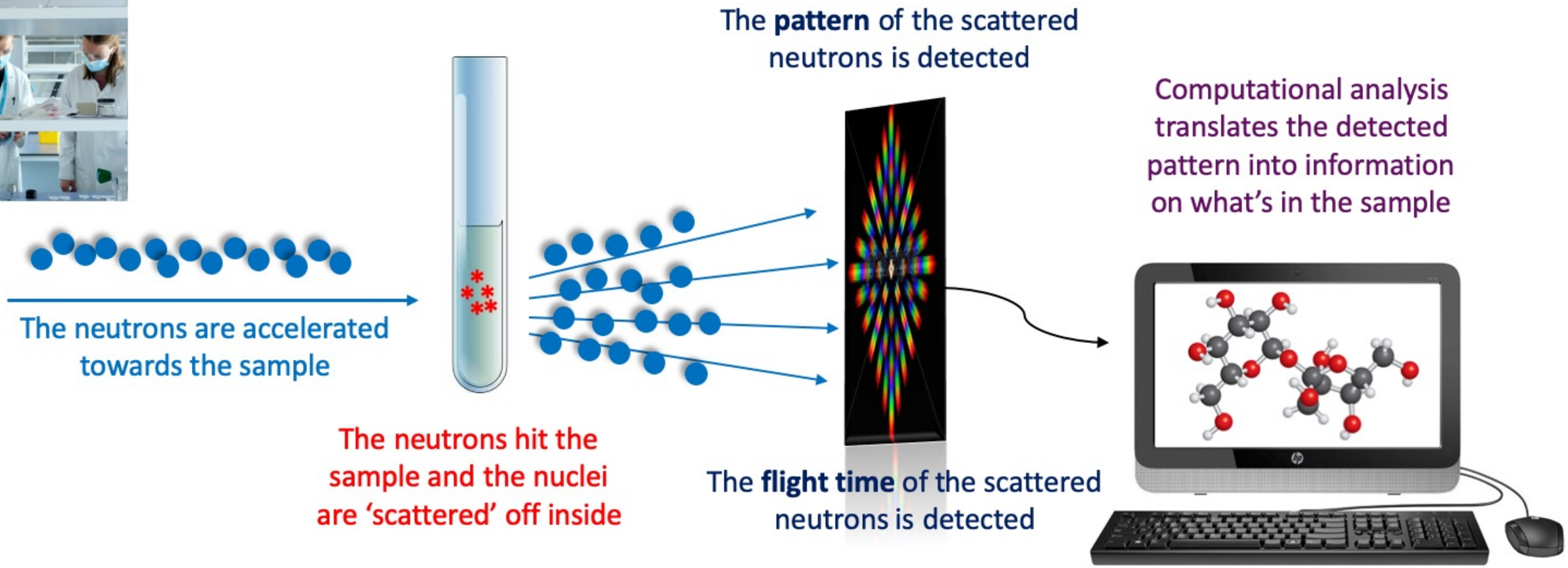


Neutron world: BrightnESS Survey

Instrument	Beamport
LoKI	N7
FREIA	N5
Estia	E2
SKADI	E3
VESPA	E7
DREAM	S3
ODIN	S2
NMX	W1
BEER	W2
CSPEC	W3
BIFROST	W4
MIRACLES	W5
MAGiC	W6
T-REX	W7
HEIMDAL	W8

Neutron scattering simplified

Labs prepare the samples locally



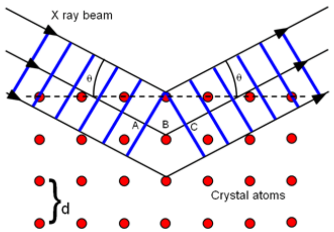
Neutrons tell us:
Where the atoms are (pattern)
What they are doing (flight time)

Sample environment to vary temperature, apply magnetic fields, pressure, humidity, in-operando processes like operating battery, welding, forging, etc.

ESS will provide support in the form of data analysis packages, user support, data storage, etc.

Diffraction - Bragg

"[Materials Physics](#)" by **Sonia Haddad presentation, ASP2018**



Using the grains as internal strain gauges

$$\lambda = 2d \sin\theta$$

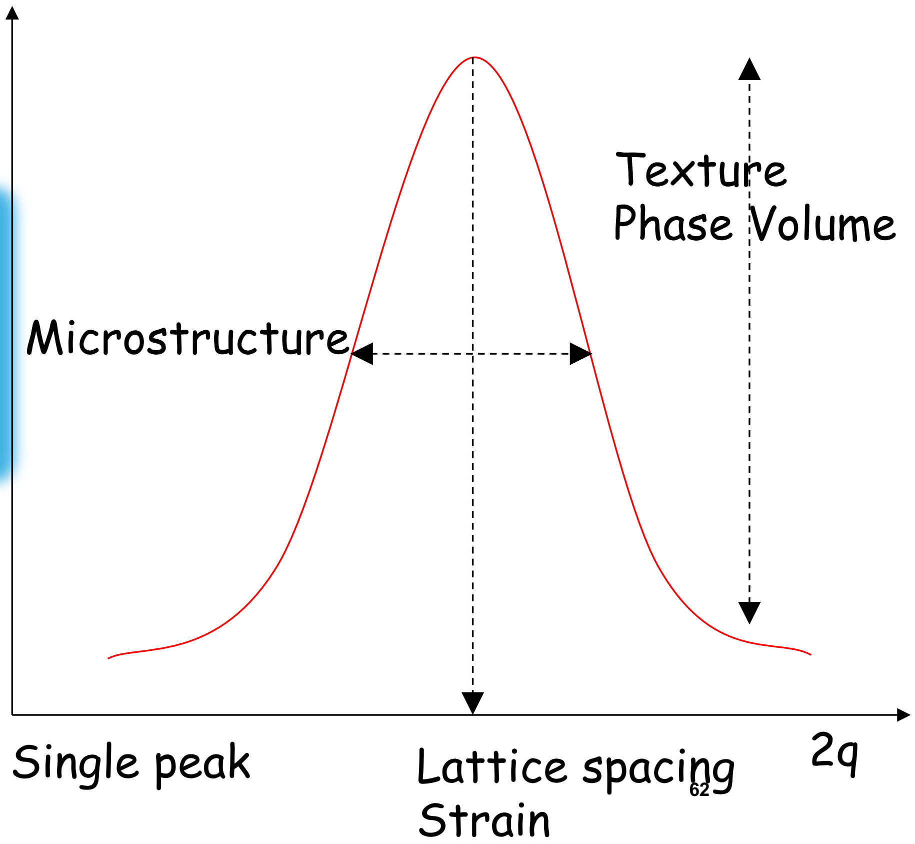
$$\varepsilon = -\cot(\theta)\,(\theta - \theta_0)$$

Two ways to measure d:

-keep λ fixed and measure θ - constant wavelength

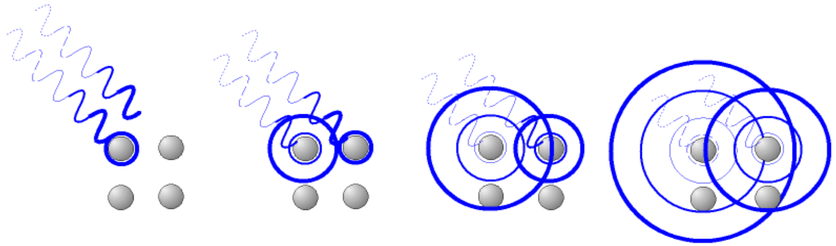
-keep θ fixed and measure λ - time-of-flight

Braggs law gives information about position of a diffraction peak from a type of lattice planes. Rietveld approach calculated height, position and width of diffraction peaks from first principles.

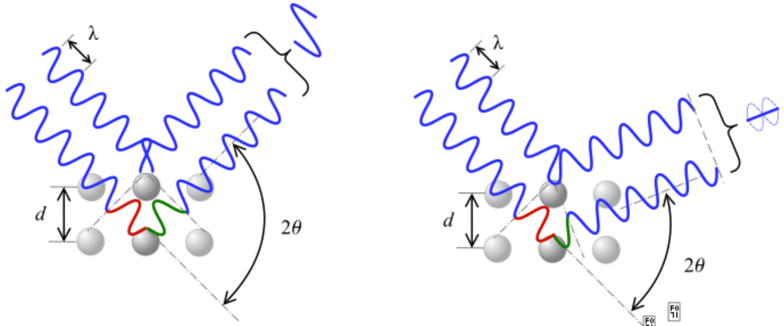


Diffraction - Bragg

Diffraction of X-rays or neutrons by polycrystalline samples is one of the most important, powerful and widely used analytical techniques available to materials scientists. For most crystalline substances of technological importance, the bulk properties of a powder
or a polycrystalline solid, averaged throughout the sample, are required; in general a single-crystal data, even if they can be obtained, are usually of little interest except for determination of the crystal structure or for studying some other fundamental physical property. By *J Ian Langford and Daniel Louer*



X-rays and neutrons interact with the atoms in a crystal.



According to the 2θ deviation, the phase shift causes constructive (left figure) or destructive (right figure) interferences.

Neutron scattering

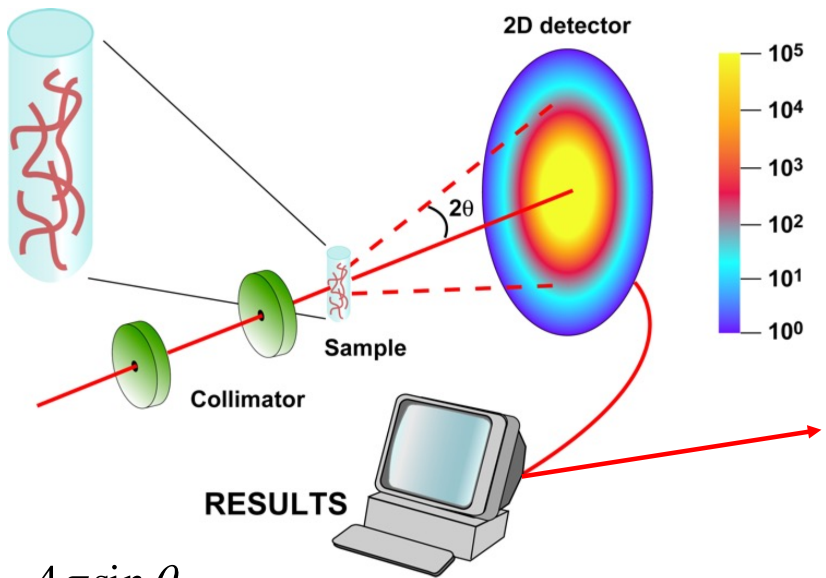
Where are the atoms and what are they doing?

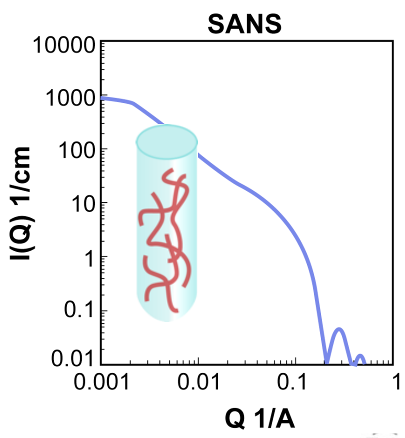
Measures structures at length scales from 1 nm to 100 nm

Beam:

Neutron (SANS)

or X-ray (SAXS)

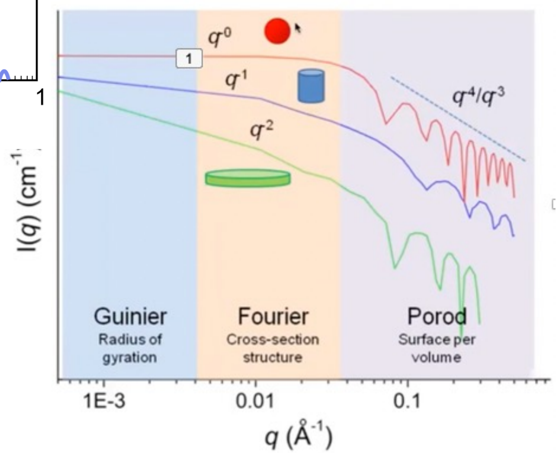




$Q_{min} \approx 0.03^\circ$
$Q_{max} \approx 3^\circ$

$$|Q| = \frac{4\pi \sin\theta}{\lambda}$$

In a standard crystallography experiment, theta_max is typically 45 degrees



"Nanoscale to Microscale Structural Analysis with Neutrons" by Judith Houston

"Neutron Sources" and further readings by CD ASP2014

Neutron Energy

$$E = k_B T$$

$$E = k_B T = \tfrac{1}{2} m v^2 = \frac{h}{2m\lambda^2}$$

$$\lambda = \frac{h}{mv}$$

Boltzmann distribution

De Broglie

$$E\,[meV] = 0.0862\,T\,[K] = 5.22\,v^2\,[km/s] = 81.81\frac{1}{\lambda^2}\,[A]$$

Source	Energy	Temperature	Wavelength
cold	0.1-10	1-120	30-3
thermal	5-100	60-1000	4-1
hot	100-500	1000-6000	1-0.4

An Integrated ESS

How does a giant microscope work?

Ion source: produce ion particles (protons)

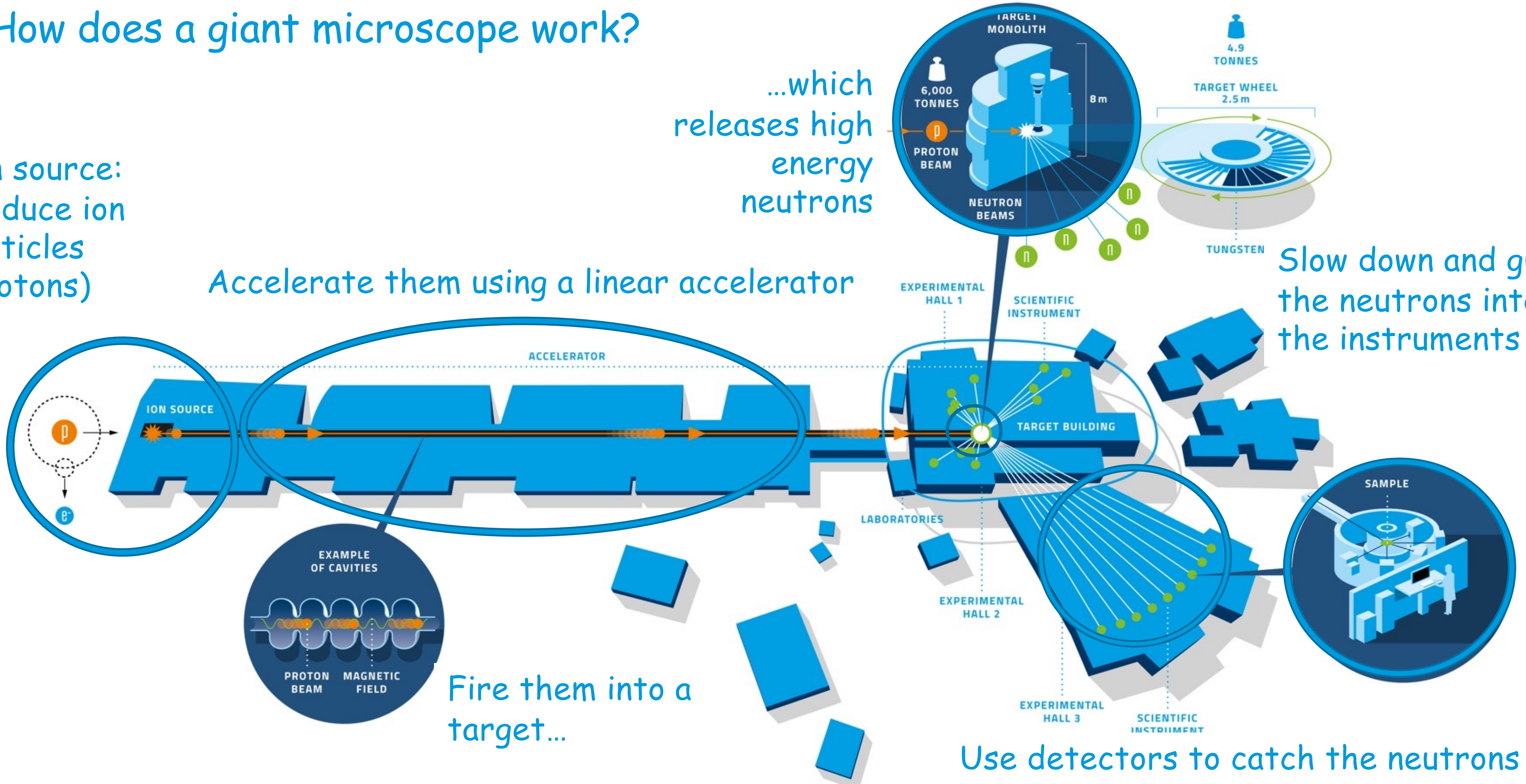
Accelerate them using a linear accelerator

Fire them into a target…

…which releases high energy neutrons

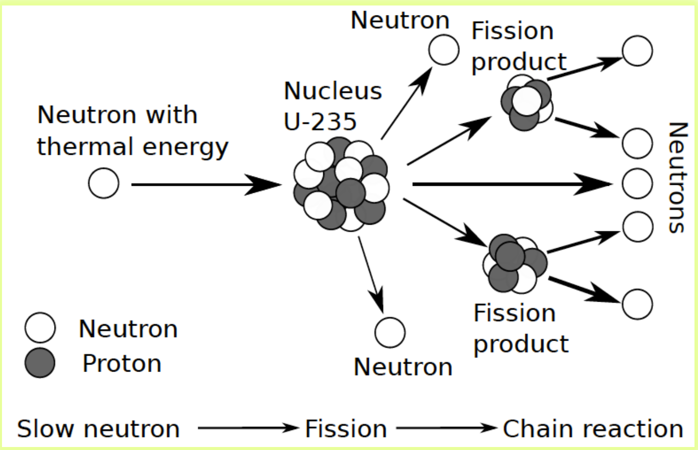
Slow down and guide the neutrons into the instruments

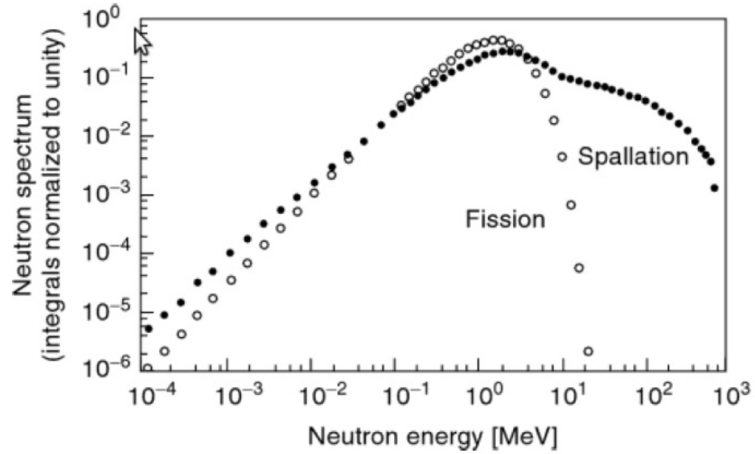
Use detectors to catch the neutrons that come out of the other end of the sample



Neutron Production !

Fission & Spallation

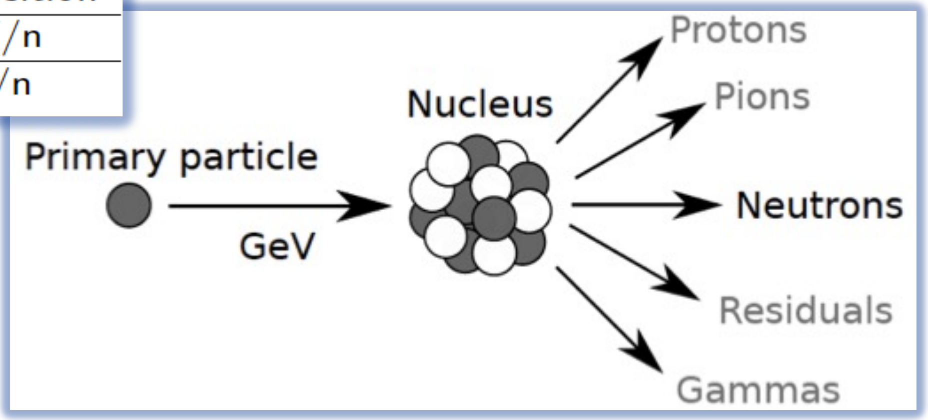




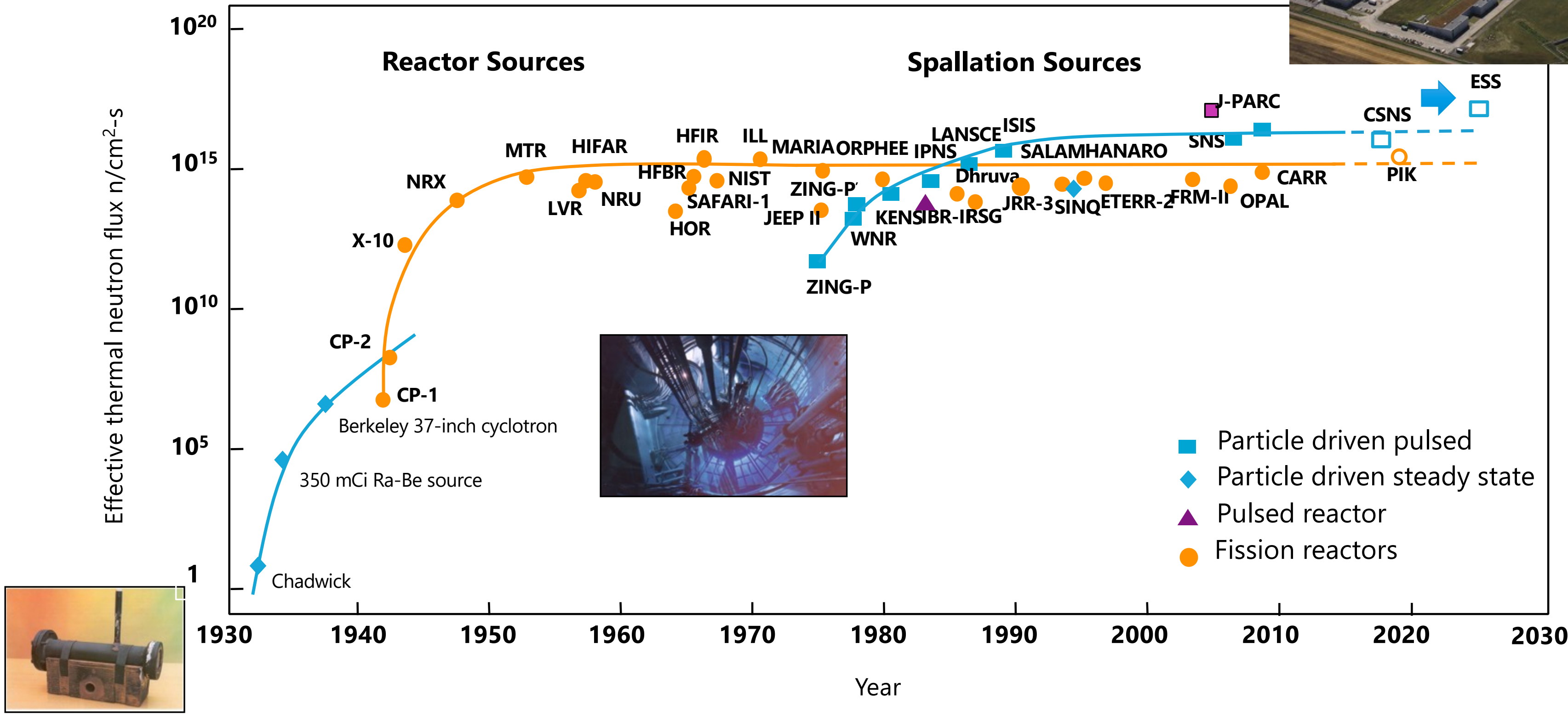
[D. Filges and F. Goldenbaum, Handbook of Spallation Research]

Spallation is a non-elastic nuclear interaction induced by a high-energy particle producing numerous secondary particles

Process	Reaction	Neutron yield	Energy deposition
Fission	$^{235}U(n,f)$	3 n/fission	190 MeV/n
Spallation	p 1 GeV → Hg	30 n/proton	55 MeV/n



High time average and peak flux



(Updated from *Neutron Scattering*, K. Skold and D. L. Price, eds., Academic Press, 1986)

Long pulse, short pulse and reactor sources
More flux needed

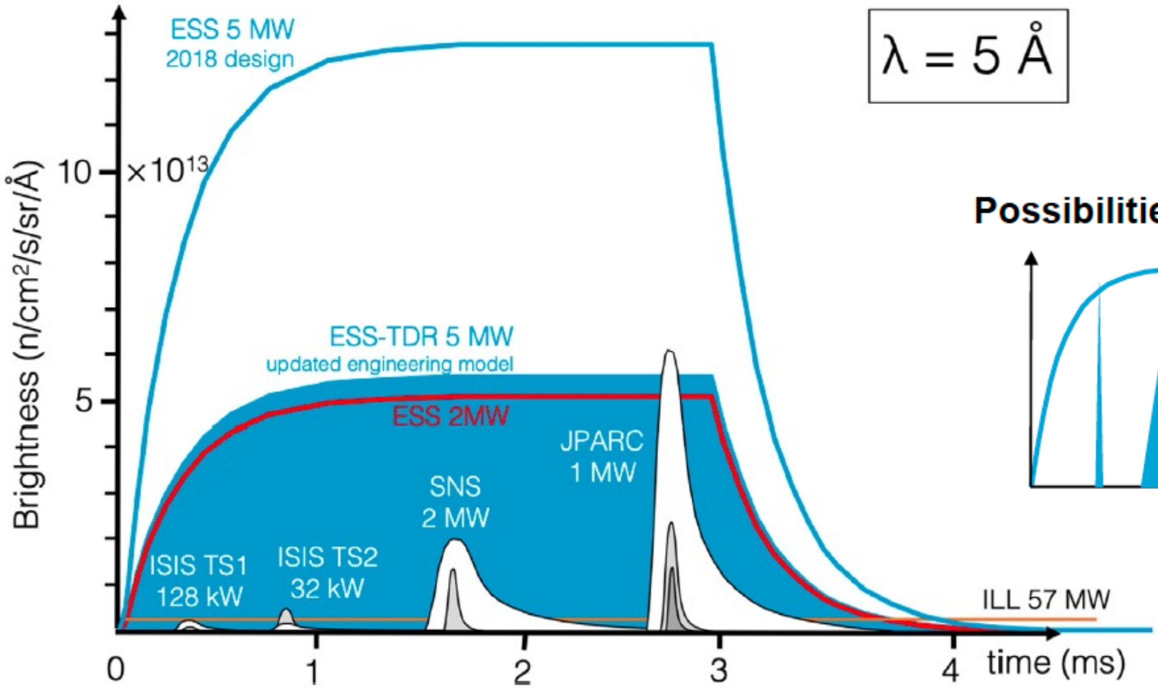
New opportunities:

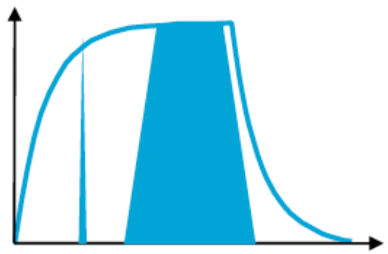
Smaller samples.

Weak effects.

Parametric studies.

Kinetic behaviour.





ESS Linear Accelerator: A Collaborative Project

Normal Conducting | Super Conducting

Key parameters:

→ 5 MW beam power (120 peak)

4 % duty cycle

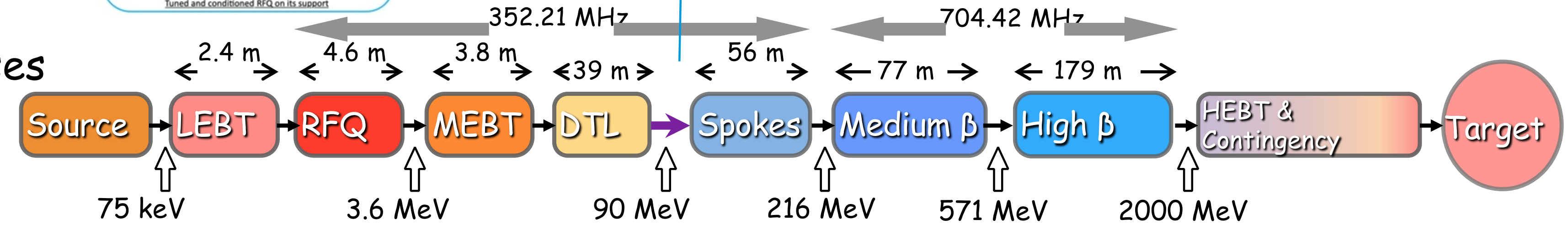
2 GeV

62.5 mA

2.86 ms long pulses

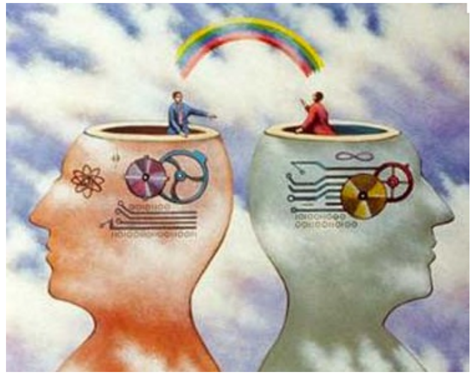
14 Hz

	Spoke	M-β	H-β
β	0.5	0.67	0.86
# CM	13	9	21
Cav. /CM	2	4	4
# Cav.	26	36	84
CM L [m]	2.9	6.6	6.6
L [m]	56	77	179



96% of acceleration will be provided by superconducting cavities supplied by dedicated high power RF sources

Concluding Comments



Developing sustainable medical accelerators necessitates a multidisciplinary approach!

Accelerators have extensive applications in healthcare, with radiation therapy being the most well-known.

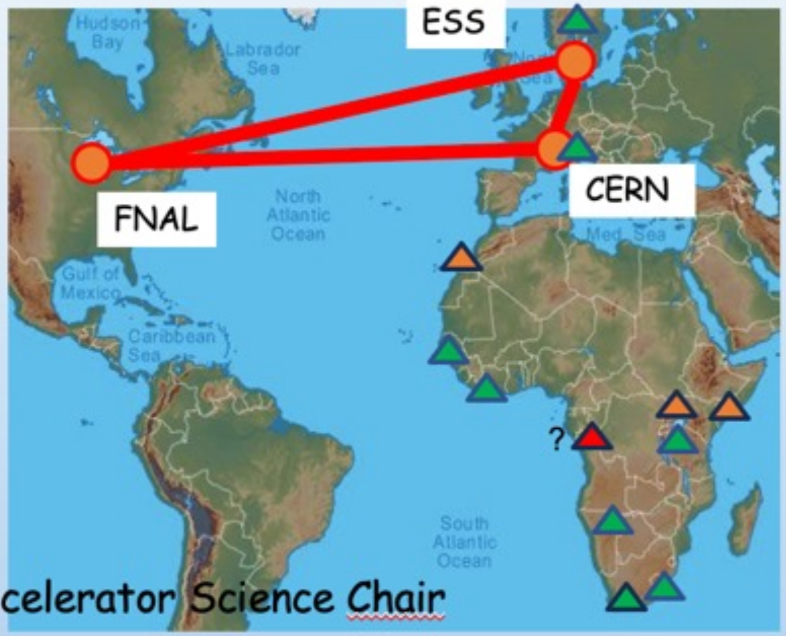
Beam times utilizing synchrotron radiation or neutron beams generated by particle accelerators are advancing basic science discoveries in life sciences!

Technology and knowledge transfer are crucial for developing this innovative ecosystem, facilitated by scientific communication, education, and collaboration.

Much more information at:
https://cdarve.web.cern.ch/

Bookmarks on cdarve.web.cern.ch/

Short bio – Christine "D'Arves"



Diplome d'ingénieur UTBM, Institut Polytechnique de Sévenans (FR), "Thermomechanical of Systems and Materials"

PhD Northwestern University (USA), "Phenomenological and Numerical Studies of Helium II Dynamics in the Two-Fluid Model"

- 25 years as Engineering Scientist at CERN, FNAL, ESS
- From design to operation of particle accelerators in large scale collaborations (incl. Large Hadron Collider, Cryogenic Magnets and Cavities, LH_2 absorber)
- In-Kind Collaborations Management

Volunteering with Non-profit organisations:

→ International Union of Pure and Applied Physics (IUPAP), WG14 Accelerator Science Chair

→ Forum on International Physics (FIP), Chair-line, American Physical Society (APS)

→ African School of Physics and Applications (ASP) Co-founder, Organiser and Lecturer

→ Nordic Particle Accelerator Program (NPAP) (schools, MOOC) Co-founder, Organiser and Lecturer

→ Physique-sans-frontieres (1998 Sc. Secretary) "WWW: A Windows on Science and Technology", Sarajevo