# Particle Accelerators for society: health, industry, environment, energy

Maurizio Vretenar, CERN

CERN | ATS Accelerators and Technology Sector

# Particle accelerators, the largest machines ever built by humankind

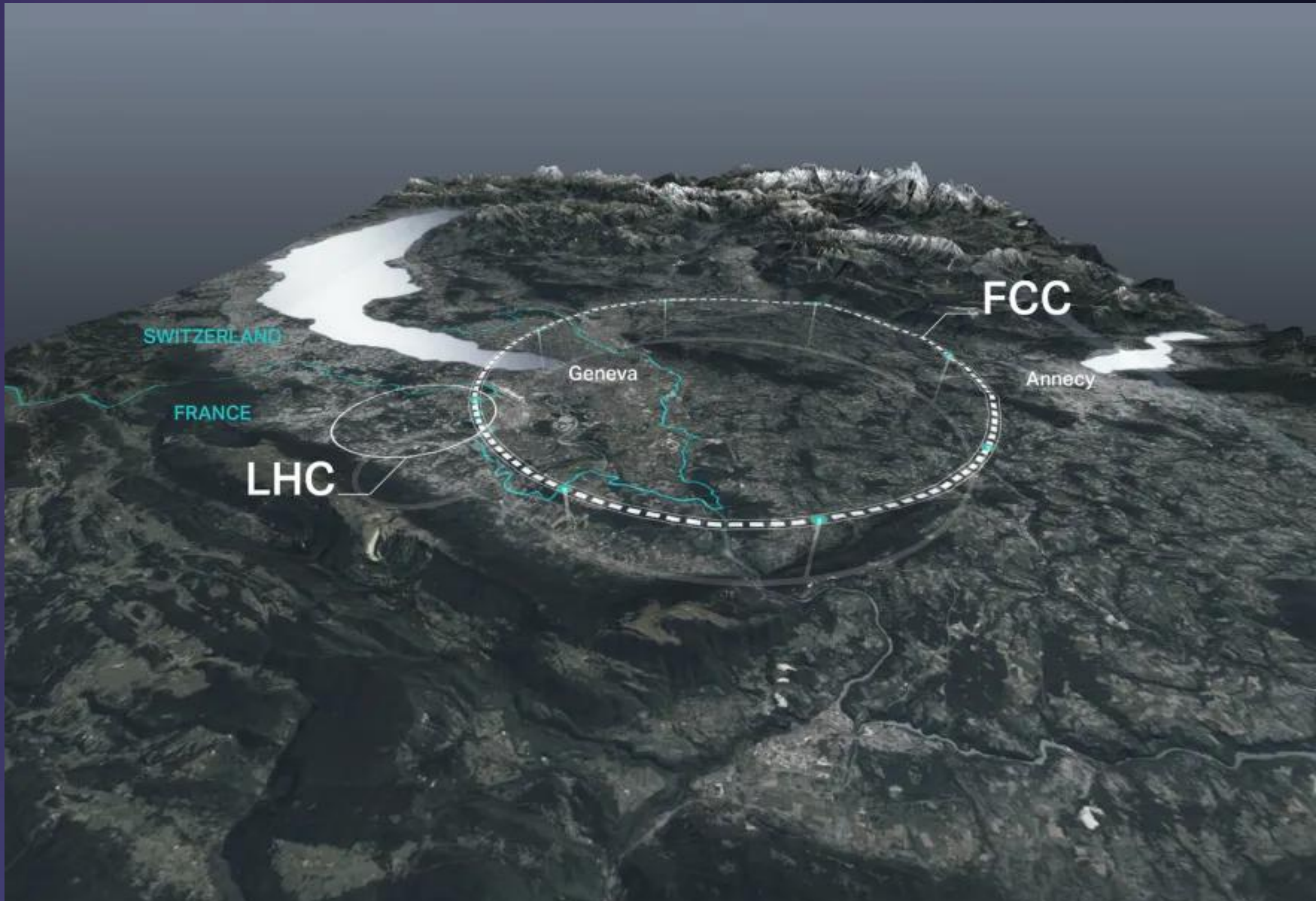
**Large Hadron Collider at CERN:**

- **27 km circumference,**
- **17 km of injectors and beam lines,**
- 100,000 m$^2$ of laboratories covering 200 hectars.

Study of a new **Future Circular Collider**:

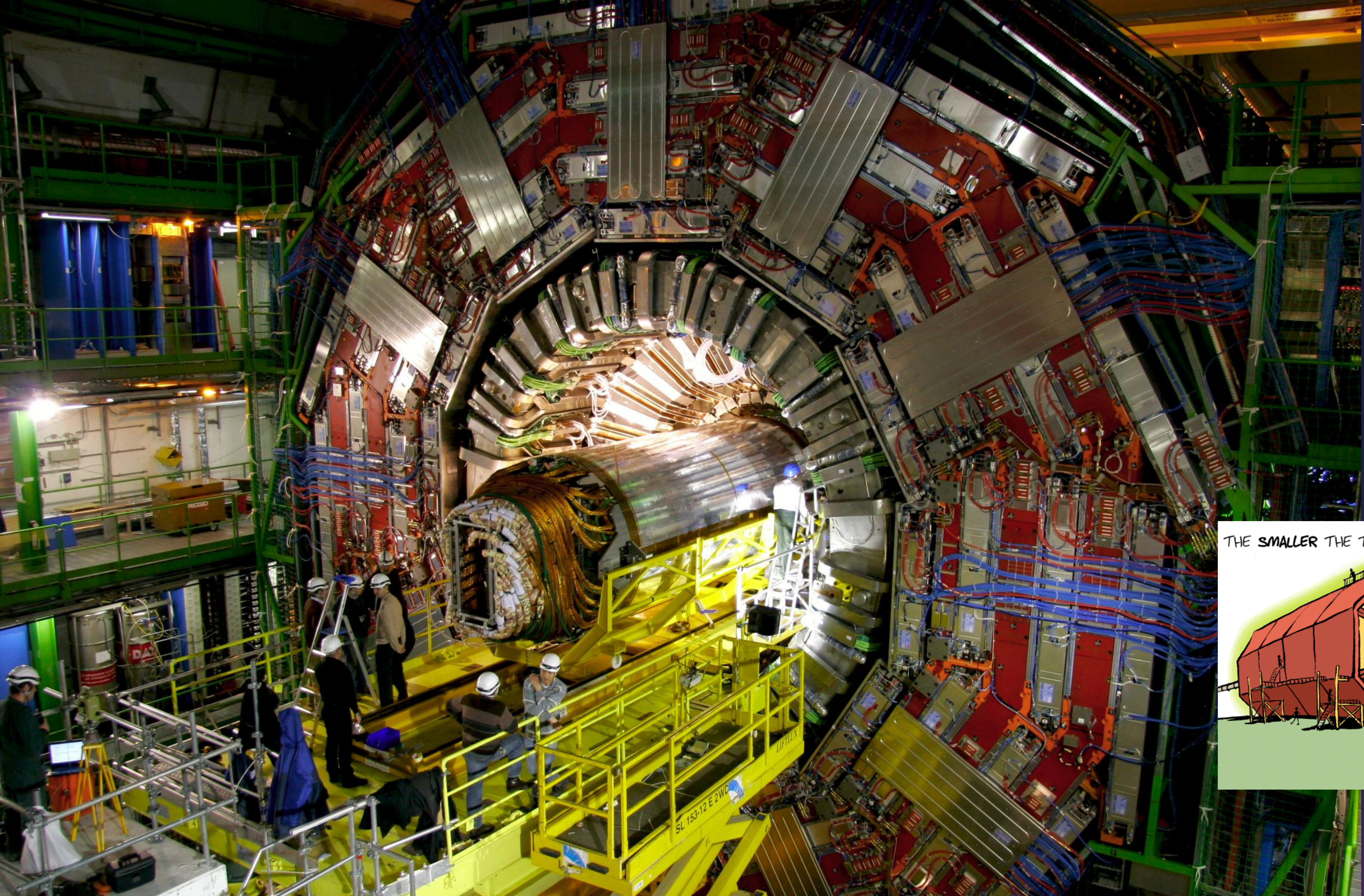
- 90.7 km of tunnel.

Guinness Book of World Records, "*The Large Hadron Collider (LHC) is the largest and most complex machine ever built.*"

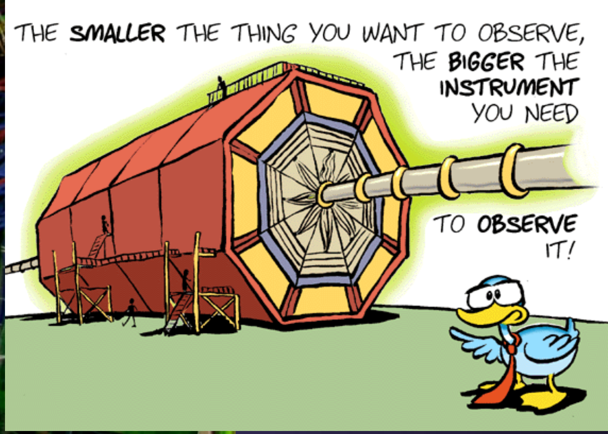



P0784

Future Circular Collider tunnel
(image: CERN)



## CMS underground detector
(image: CERN)



# Accelerators are everywhere, not only in scientific labs

Radiotherapy linear accelerator to treat cancer

17,000 in operation

*Image credit: Siemens Healthineers Med Museum*

Linear accelerator for ion implantation

~12,000 in operation

*Image credit: Axcelis Technologies*

Cyclotron for radioisotope production

~1,800 in operation

*Image credit: IBA*

Rhodotron electron accelerator for industrial applications

*Image credit: IBA*

# Particle accelerators for society

Nearly 40'000 particle accelerators in operation around the world:

- only 6% for research (0.5% particle physics)
- 94% for medicine and industry

Counting only >100 kV accelerators, excluding the old TV tubes that are all electron accelerators.

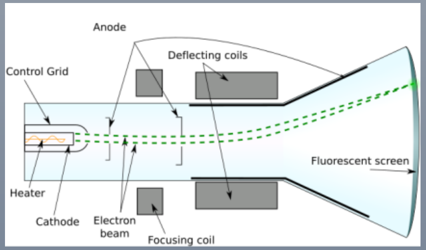



Image credit: Wikimedia commons

| | | |
|---|---|---|
| **Research** | | **6%** |
| | Particle Physics | 0,5% |
| | Nuclear Physics, solid state, materials | 0,5% |
| | Biology | 5% |
| **Medical Applications** | | **35%** |
| | Diagnostics/treatment with X-ray or electrons | 33% |
| | Radio-isotope production | 2% |
| | Proton or ion treatment | 0,1% |
| **Industrial Applications** | | **60%** |
| | Ion implantation | 34% |
| | Cutting and welding with electron beams | 16% |
| | Polymerization | 7% |
| | Neutron testing | 3.5% |
| | Non destructive testing | 2,3% |

# Why so popular?

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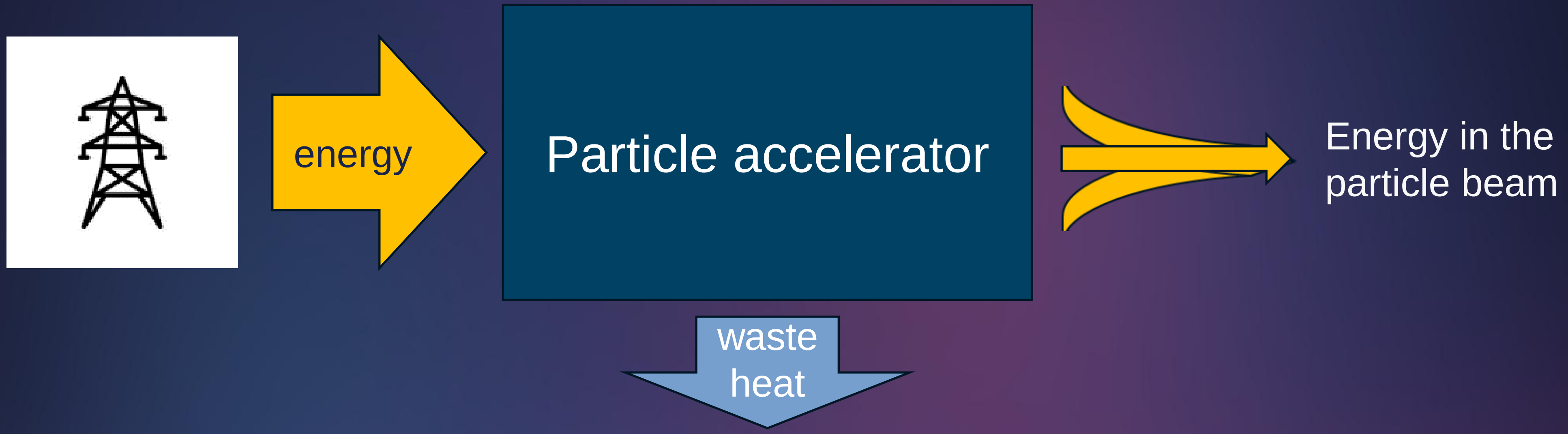
## A particle accelerator is an **instrument** to concentrate energy at subatomic scale



# How large is the energy? Let’s try a small contest

| | LHC proton | LHC bunch | yoghurt | high-speed train |
|---|---|---|---|---|
| | |  |  |  |
| **Energy** | $1.1\ 10^{-6}$ J | $1.3\ 10^{5}$ J | $5\ 10^{5}$ J | $1.4\ 10^{9}$ J |
| **Energy Density** | $5.3\ 10^{38}$ J/m$^3$ | $0.5\ 10^{12}$ J/m$^3$ | $3.3\ 10^{9}$ J/m$^3$ | $7.0\ 10^{5}$ J/m$^3$ |

The unit: Joule (J)
1 J is really small,
=1 Ws , cost $10^{-7}$ €.

- *Proton: 7 TeV, classic radius*
- *Yoghurt: 150 g, 120 cal.*
- *Train: 400 tons, 200 m, 300 km/h*
- *Bunch: $1.15\ 10^{11}$ protons at LHC interaction point.*

*For comparison: Li-ion battery $6\ 10^{9}$ J/m$^3$, Diesel fuel $4\ 10^{10}$ J/m$^3$*

**Particle accelerators are instruments that concentrate huge amounts of energy at atomic and subatomic scale**

# Where does the energy go?

The accelerated particle can:

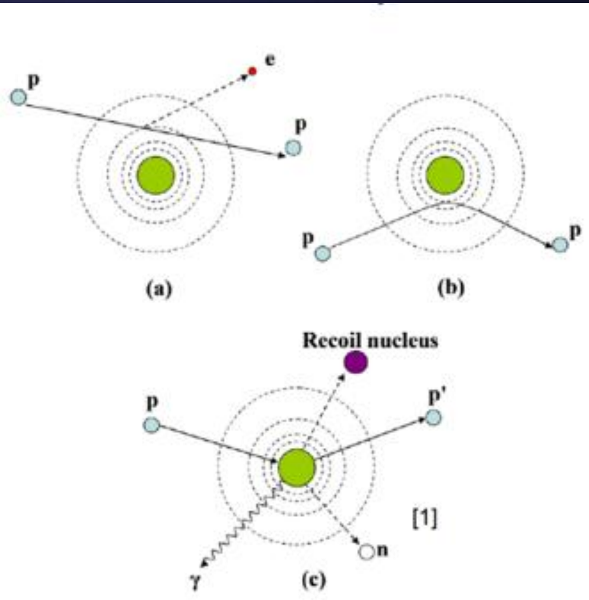
a) kick electrons out of the atom (**ionization**): breaking of molecules, generation of free chemical radicals acting at chemical and molecular level.

**b) Excite** electrons to a higher energy level, that coming back generate **X-rays**.

**c) Give energy** to the atomic nuclei.

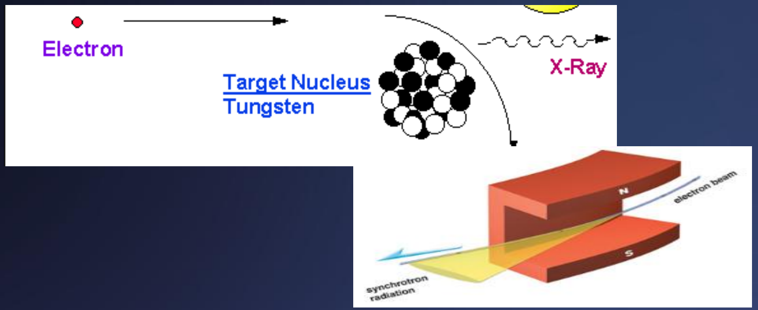
d) Break/modify the **nucleus**, generating secondary particles.

e) Interact with other subatomic particles, generating **new particles**.

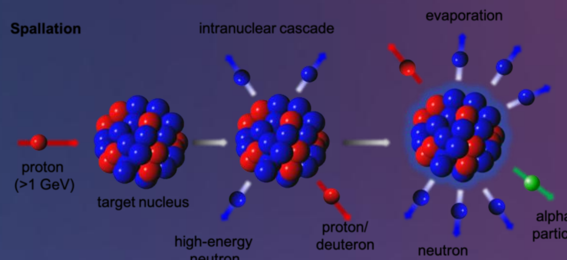



Secondary beams, e.g. X-rays or neutrons, for applied science and medicine.

*X-rays: bremsstrahlung or synchrotron light*

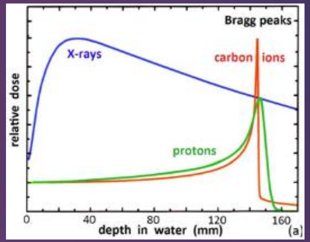



*Neutrons: spallation or other reactions*

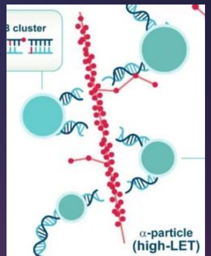



Particle-driven chemical processes in medicine, environment.

*Penetration dependent on beam energy*



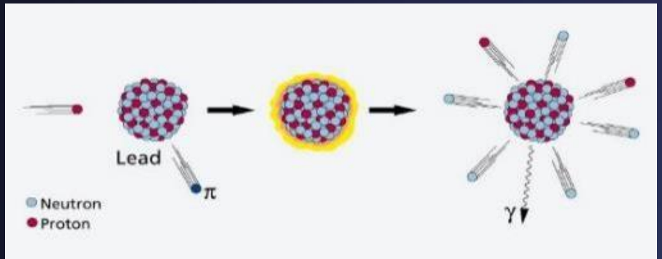

*Break molecules or DNA*



# Accelerators as dream machines

Every technology starts from a dream, and accelerators have been invented to fulfil two old human dreams

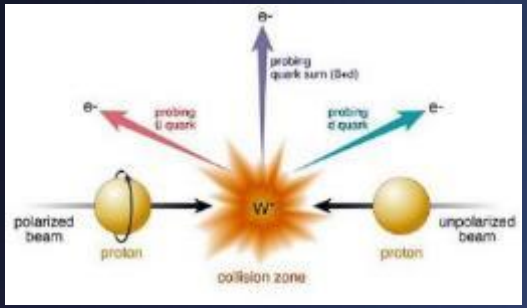
The dream of NUCLEAR PHYSICS

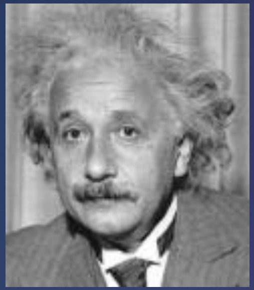



Particles can break and modify the nucleus, generating new atomic elements and transforming matter

Transforming matter, the dream of ancient alchemists

The dream of PARTICLE PHYSICS



$E = m c^2$

In high-energy collisions, energy can generate new particles

The magic of creating matter

# A new dream, bloodless medicine

Accelerators are increasingly being used in medicine, as **nuclear scalpels** that allow to observe and cure the inner parts of the body without pouring blood (bloodless therapy!)

*The dream of bloodless MEDICINE*

Particles deposit energy at a well-defined depth without damaging surrounding tissues.

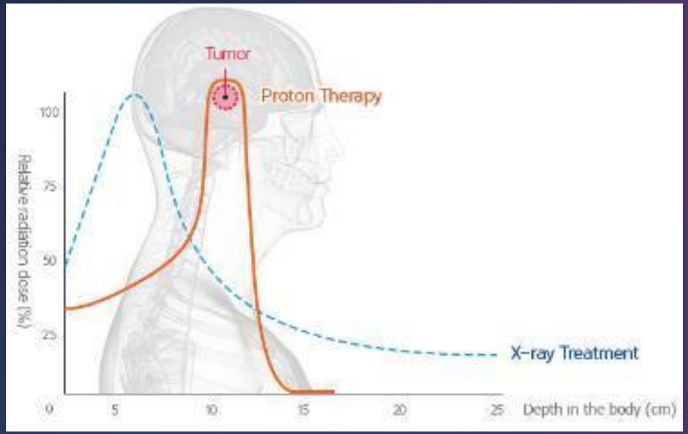


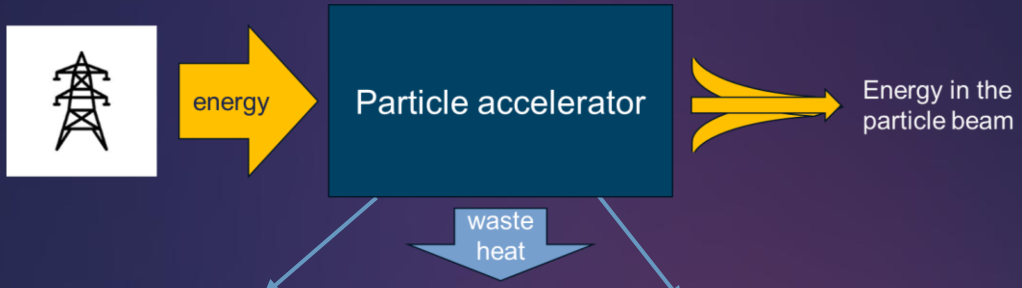

Image credit: Lim, D., Radiation Therapy against Pediatric Malignant Central Nervous System Tumors : Embryonal Tumors and Proton Beam Therapy, 61, Journal of Korean Neurosurgical Society, https://creativecommons.org/licenses/by-nc/4.0/

Treatment and imaging using accelerators

Particles and X-rays

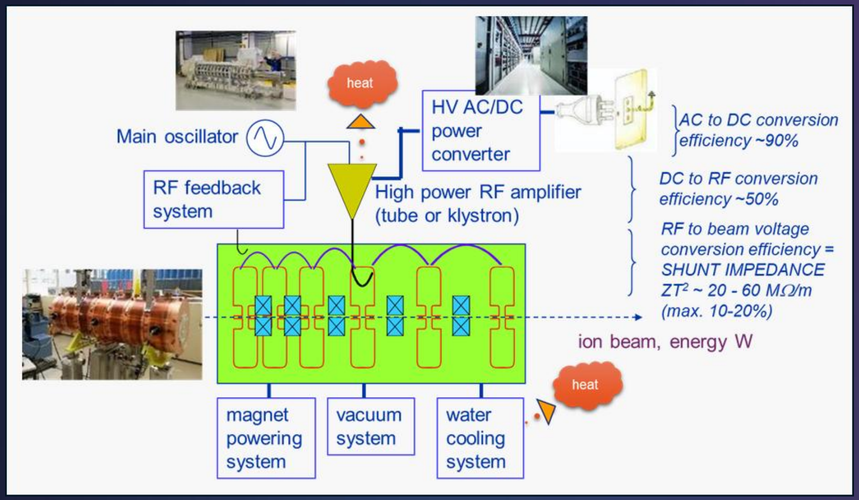
Observing and curing the body without blood

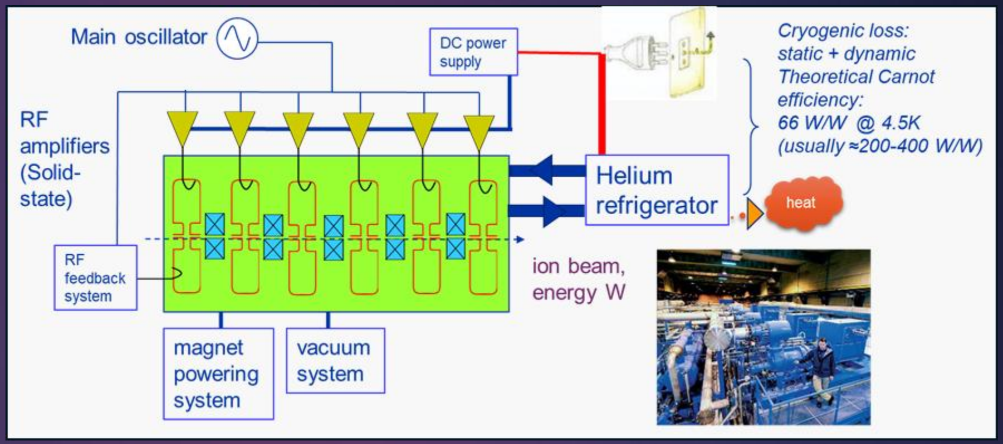
# A basic limitation: energy quality and energy efficiency




Normal conducting accelerator

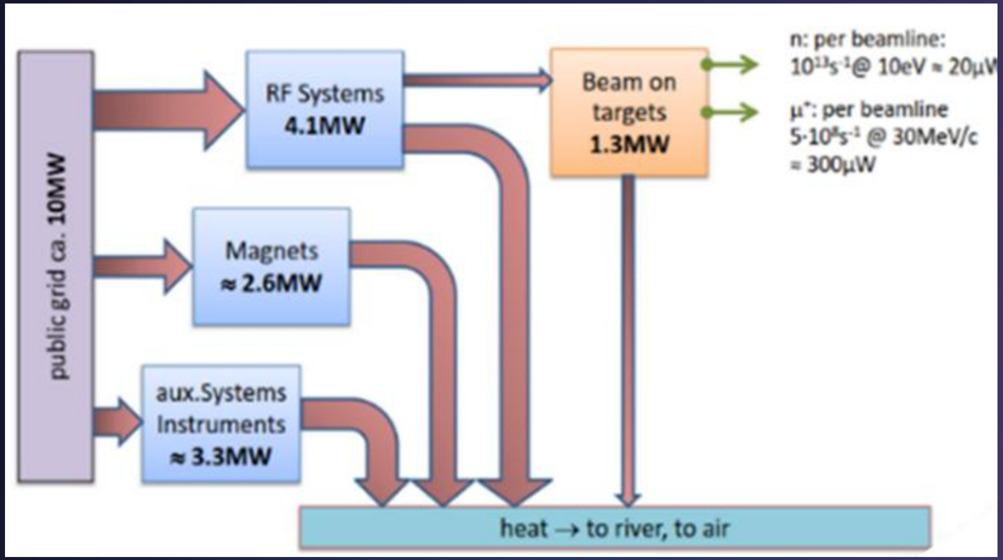
Superconducting accelerator




Accelerators convert energy from the electricity grid into high-quality energy concentrated in a particle beam at subatomic scale. Energy goes through several conversions, each with its own (<1) efficiency, limited by fundamental as well as practical factors. Only a small fraction of the energy is converted into beam energy.

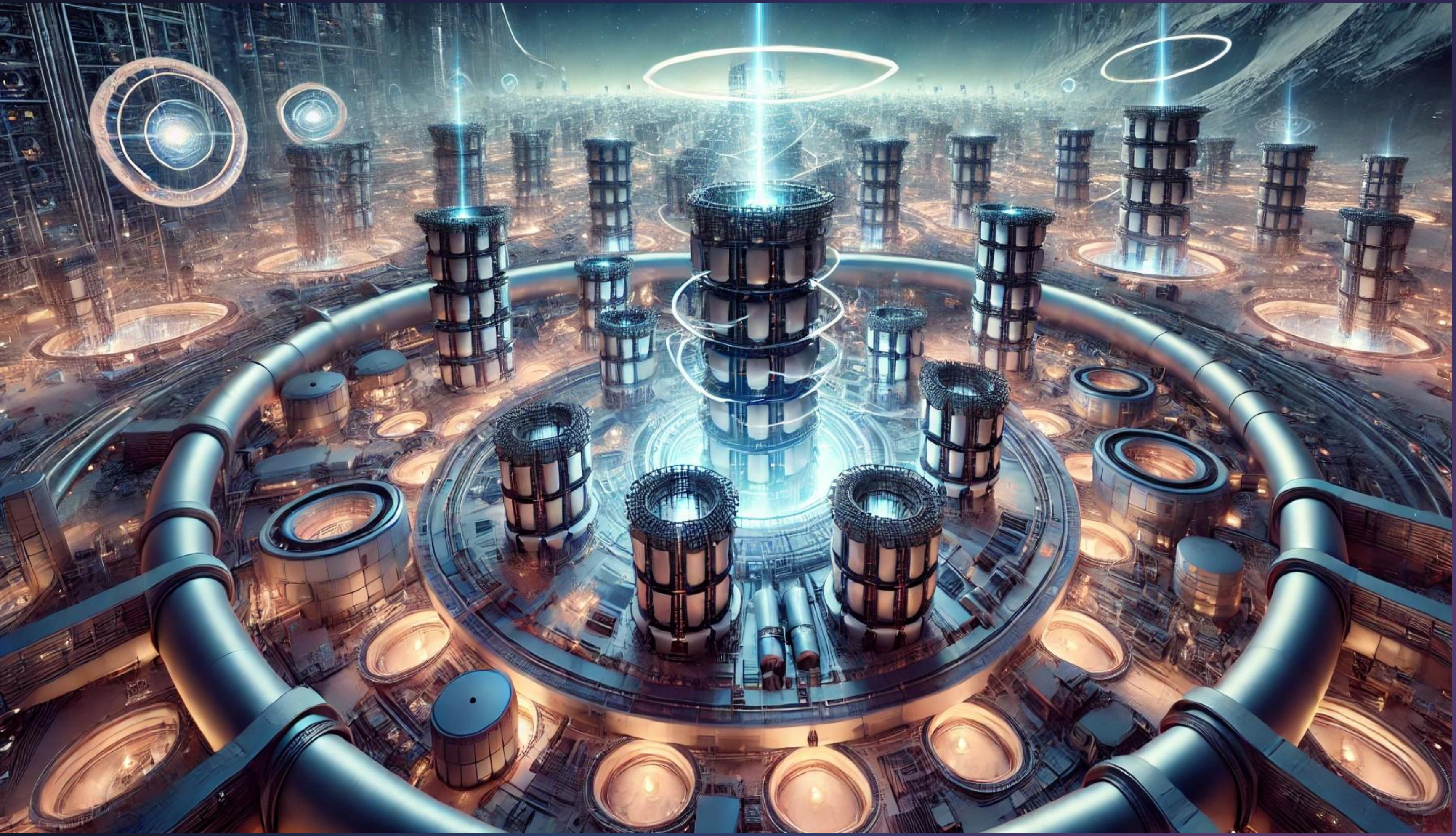
# Accelerators: very precise but expensive tools




Energy flow in the PSI cyclotron
(J.K. Grillenberger et al., The Energy Efficiency of High Intensity Proton Driver Concepts, IPAC17)

Most of the energy to the accelerator is dissipated in the cooling water used to remove heat from the components.
On the left, overall energy flow in the PSI cyclotron for production of neutrons and muons → Grid-to-beam efficiency 13%.
Accelerators for particle physics have even lower efficiencies, related to the higher quality of the beam required to produce the collisions.
Specially designed superconducting linac systems for high-intensity beams can reach efficiencies close to 50%.
Concentrating energy into a particle beam creates a drastic local reduction in entropy, that must be paid for with a strong energy dissipation.

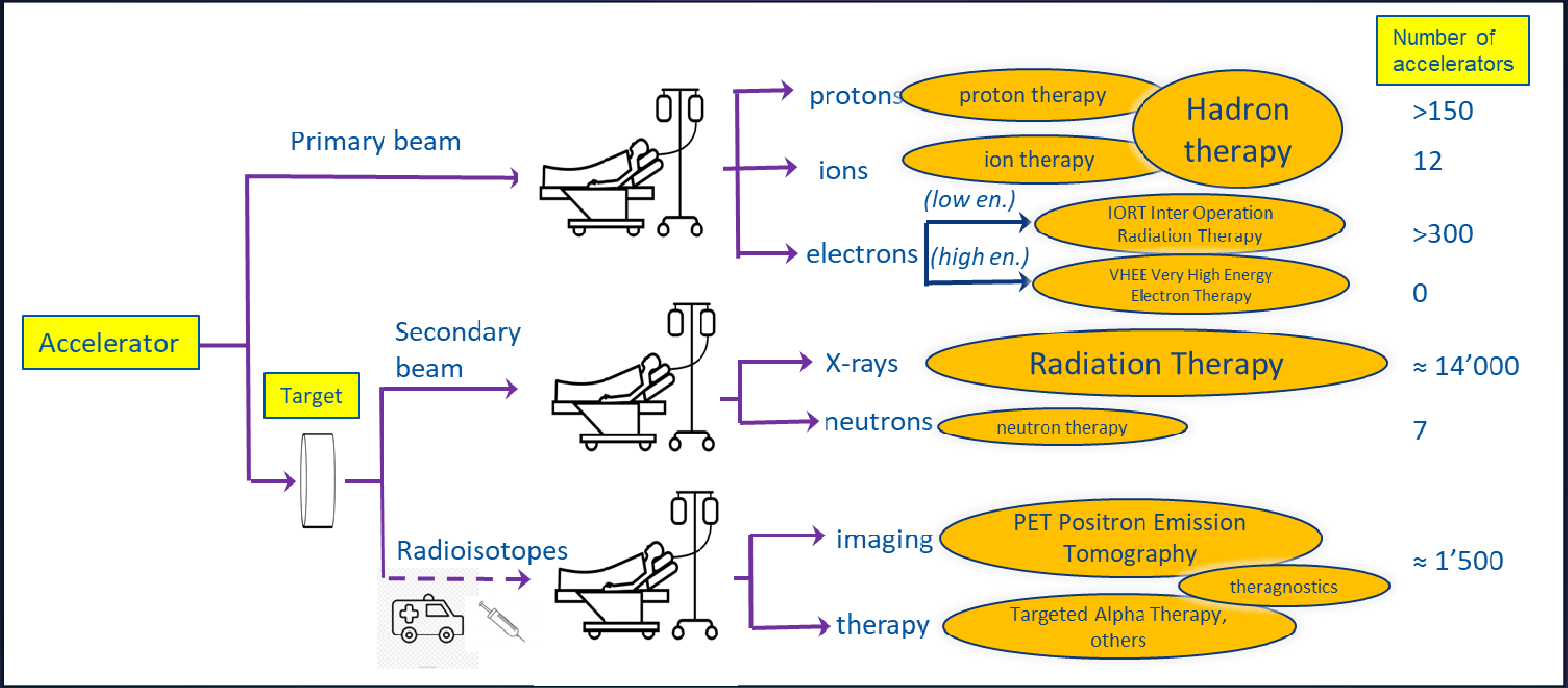
Energy density in the beam is high, but total energy is relatively low and comes at a high cost in terms of energy from the grid → accelerators cannot be efficiently used for large scale industrial processes, but only for small scale processes requiring high precision at atomic or subatomic scale.



# Where do we find accelerators?

Chat GPT vision of “a landscape of particle accelerators”

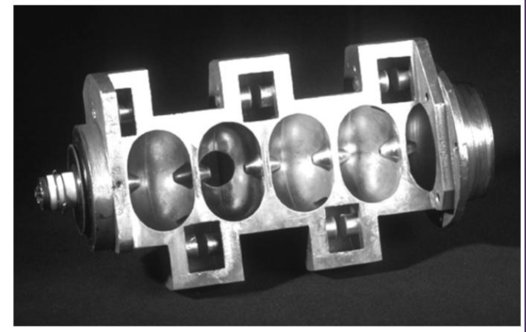
# Accelerators for medicine



# X-ray radiotherapy linac, the pillar of cancer therapy

~50% of all cancer patients require radiotherapy during the course of their disease (Atun et al., 2015; Jaffray et al., 2015)

A short electron linear accelerator (0.5 – 2 m) at energies 5 – 20 MeV produces X-rays by bremsstrahlung in a tungsten target.



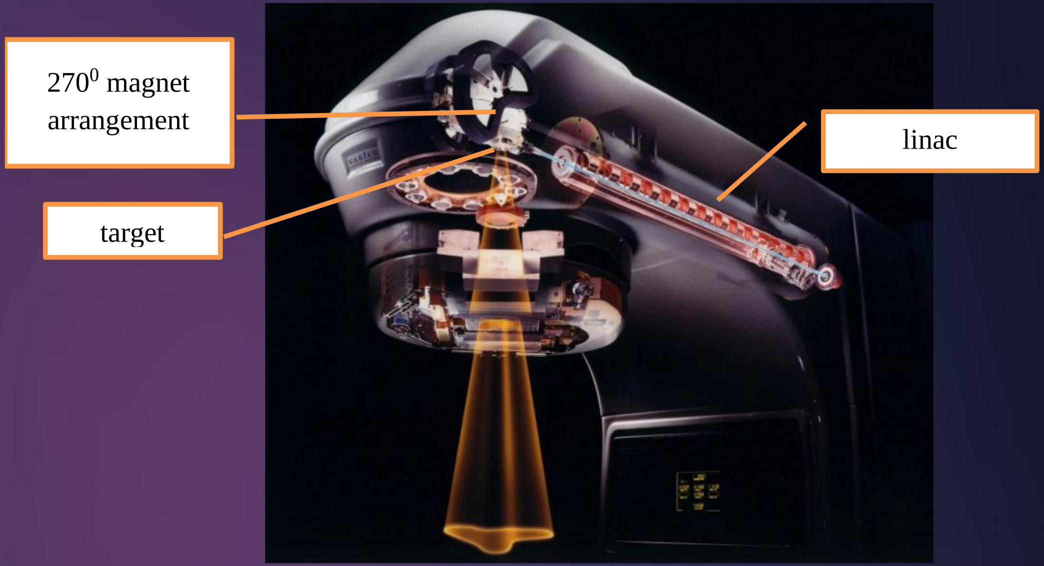


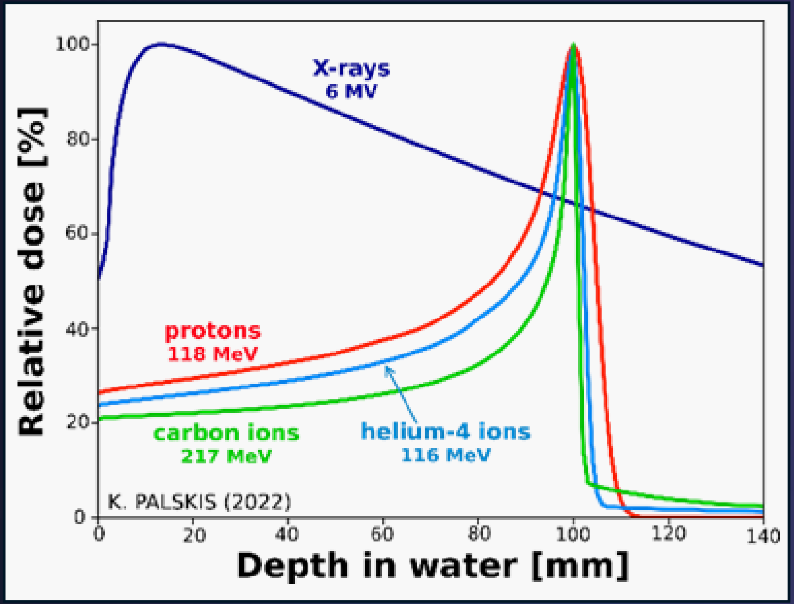

*Image credit: Varian Medical Systems, Inc.*

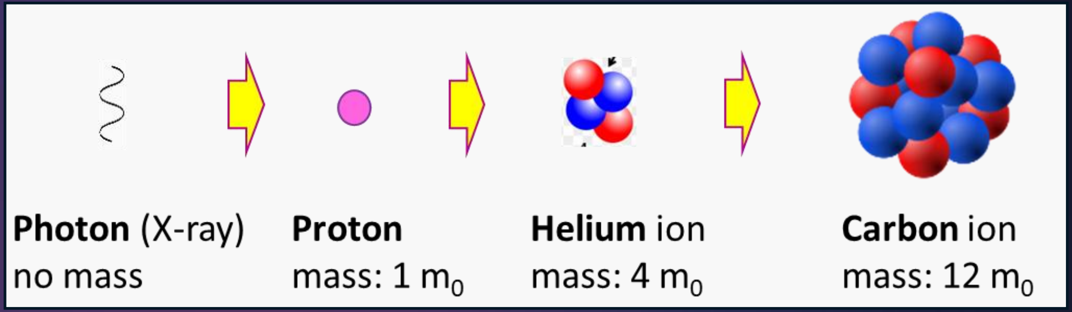
Nearly 17,000 in operation worldwide
(https://dirac.iaea.org/)

*Side-coupled standing-wave linac structure, developed in 1967 for the Los Alamos Meson Facility. Thanks to its efficiency and stability equips most of present radiotherapy linacs*

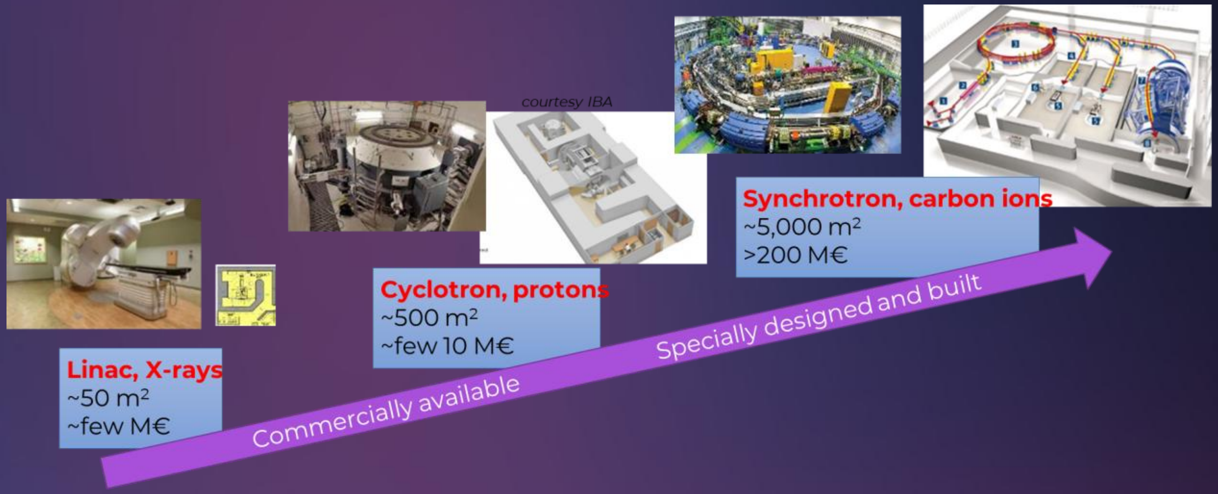
Good example of technology transfer from scientific to industrial accelerators

# Treating cancer with beams: X-rays, protons, carbon,…



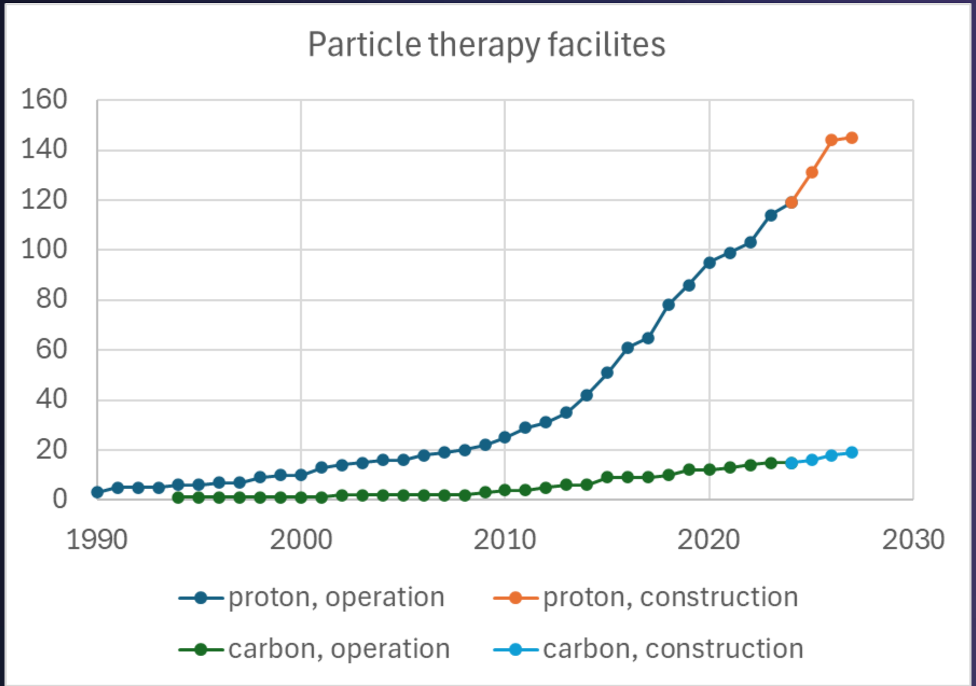




Ions deliver more energy to the tissues but need more energy to enter the body → factor 2.8 in accelerator diameter from protons to carbon




**Bragg peak:**
Different from X-rays or electrons, protons (and ions) deposit their energy at a given depth inside the tissues, **minimising the dose to the organs close to the tumour**.

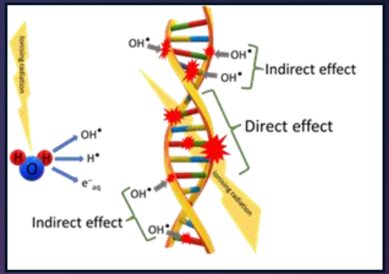
# Particle therapy, the “nuclear scalpel” of XXI century




119 proton and 16 carbon ion therapy facilities in operation worldwide (2024)
(https://www.ptcog.org)

- Protons or ions: a **precision “scalpel”,** to be handled with care.
- Biophysics research, new clinical trials, improved diagnostics and delivery tools are increasing the diffusion and reach of particle therapy.
- Recommended for several types of cancer, in particular close to critical organs or in pediatrics. Clear advantage in reducing side effects → improved **quality of life**.
- Interesting indications from coupling particle therapy with immunotherapy.

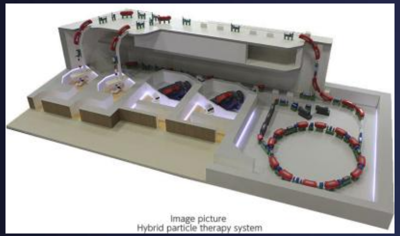
Electrons and protons act at chemical level, carbon induces double-strand DNA breakings effective on “radioresistant” cancers.



# New accelerators for particle therapy

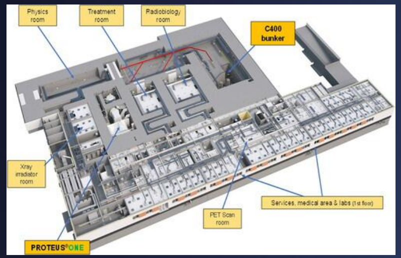
## Commercial carbon ion therapy

After years of developments, two companies can now provide complete large carbon ion therapy accelerator systems.




https://www.hitachi-hightech.com/global/en/products/healthcare/treatment/pbt/hybrid.html

Hitachi is building the first US carbon centre in Florida (Mayo Clinic)

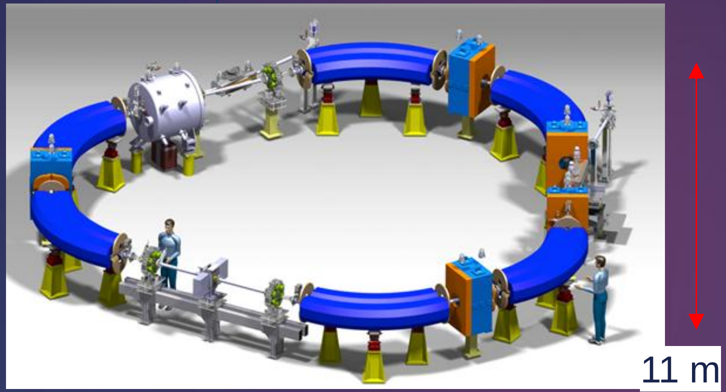



Chevalier, F. et al., (2022). CYCLHAD: A French Facility Dedicated for Research and Treatment in Hadrontherapy. Nuclear Physics News, 32(2), 27–31.

IBA is building the first superconducting cyclotron for carbon therapy at Caen (F)

## Accelerators for helium therapy

Helium offers better conformality than protons with lower dose to healthy tissues.
Clinical trials starting at Heidelberg Ion Therapy (D).




M. Vretenar. et al., (2023). Conceptual design of a compact synchrotron-based facility for cancer therapy and biomedical research with helium and proton beams, IPAC23 Conference, https://cds.cern.ch/record/2887018/files/document.pdf

Design of a compact triangle-shaped synchrotron for therapy with helium and protons (CERN)

## Very High Energy Electrons for FLASH therapy

Recent experiments indicate that ultra-high dose rates can spare healthy tissues. Coupled with high-energy electron accelerators, may open a new avenue to cancer treatment.

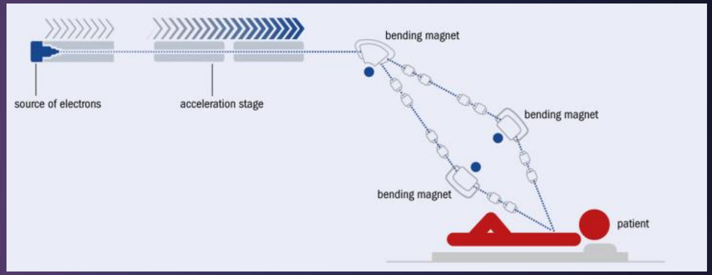



Image credit: CERN Courier, 2020

Design of FLASH-therapy accelerator systems ongoing – CERN approach based on high-frequency technology from the CLIC linear collider.

# Radioisotopes and theragnostics: nuclear chemistry and engineering

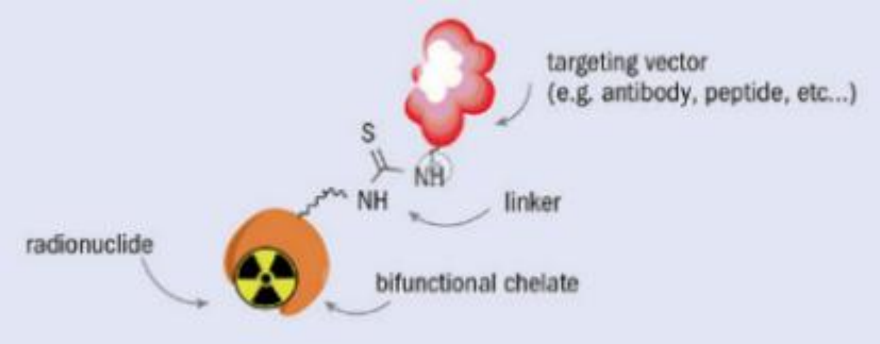



*Image credit: CERN Courier*

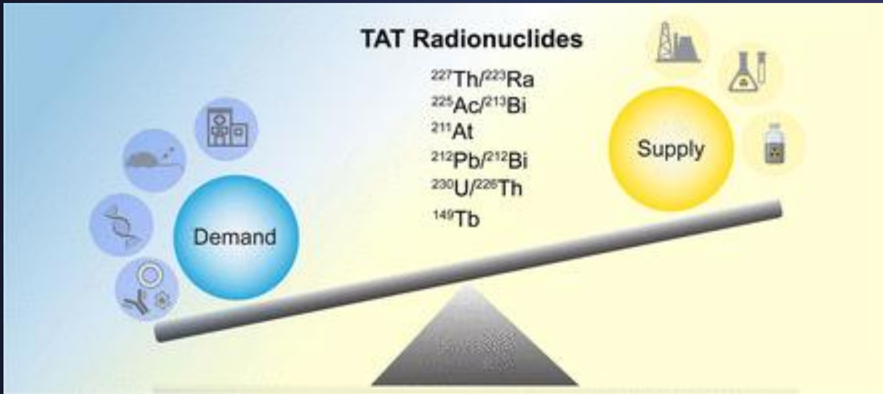



Image credit: V. Ratchenko, Journal of Nuclear Medicine November 2021, 62 (11) 1495-1503

Radioactive tracers made using accelerator-produced radioisotopes are widely used in medical imaging: PET scanning (18F), SPECT., etc.

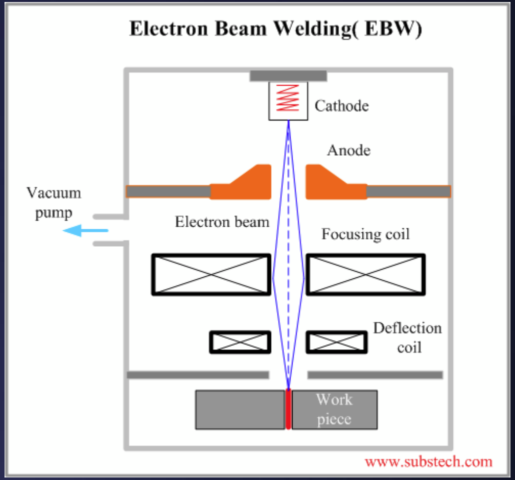
A new era for nuclear medicine is starting, using radioisotopes not only for imaging but also for locally treating cancer and other diseases (**theragnostics**).

**Example: Targeted Alpha Therapy (TAT)**
Alpha particles are localised killers, with short range and high toxicity. Accelerator-produced alpha emitters are attached to antibodies and injected to the patient. The targeting vector accumulates the isotopes in the cancerous tissues where they selectively deliver their dose. Advanced experimentation, promising for solid or diffused cancers (leukaemia).

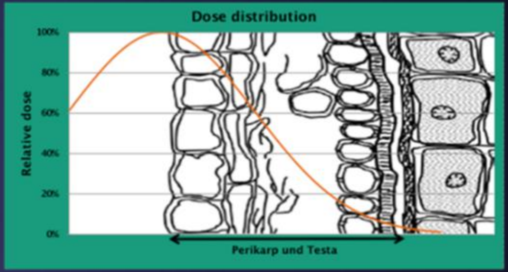
Expectations for a strong demand of compact accelerators for production of alpha emitters – close to hospital, to use isotopes with short-lifetime.

# Accelerators for industry

| | Energy | Applications |
|---|---|---|
| Very low energy electrons | <350 keV | detection, welding, 3D-sintering, sterilisation, seed and grain treatment |
| Low-energy electrons | <10 MeV | polymer modification, sterilisation, treatment of flue-gas, wastewater, sewage |


- Non-thermal: breaking molecular bonds, chemical modifications of organic materials, creation of radicals.
- Thermal: melting, evaporation, welding, joining, drilling, hardening, sintering,…




- **Cross-linking** of polymers to increase resistance and durability: insulations, heat shrinkable packaging films, polyethylene foams, tire components.
- **Electron Beam Welding** to join metallic parts without deformation.
- **Food sterilization:** breaking of molecular bonds associated with water and DNA in microbial cells.

**Seed and crop treatment –** *20 to 30% of food harvested is lost to rotting and insect infestation*
Standard treatment: chemical seed dressing with possible contamination of soil and ground water.
Alternative: physical disinfection of seed using the **biocidal effect of accelerated electrons**. Radiation on surface without damaging the DNA.

LIMITATION to sterilization: low social acceptance of “radiation” technologies

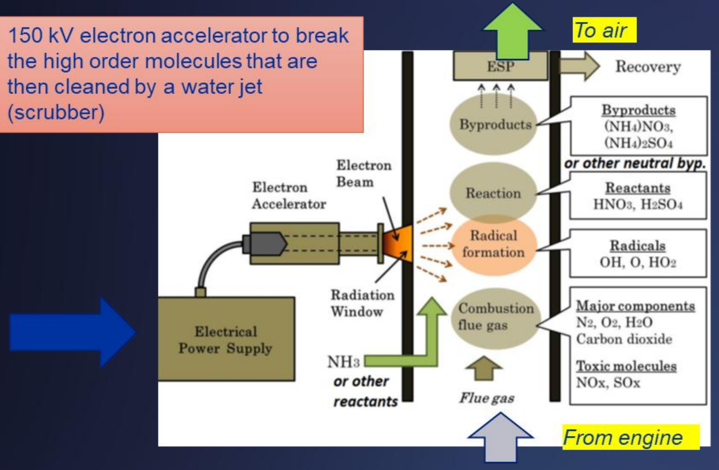
# Accelerators for the environment

Low-energy electrons can break molecular bonds and used for:
- Flue gas treatment (cleaning of SOx from smokes of fossil fuel plants)
- Wastewater and sewage treatment
- Treatment of marine diesel exhaust gases (removal of SOx and NOx).

Several experimental systems built, economics being studied

Example: HERTIS (Hybrid Exhaust Gas Cleaning Retrofit Technology for International Shipping) testing at Riga shipyard, 2019. Goal: reduce SOx and NOx emission from maritime diesel engines

150 kV electron accelerator to break the high order molecules that are then cleaned by a water jet (scrubber)





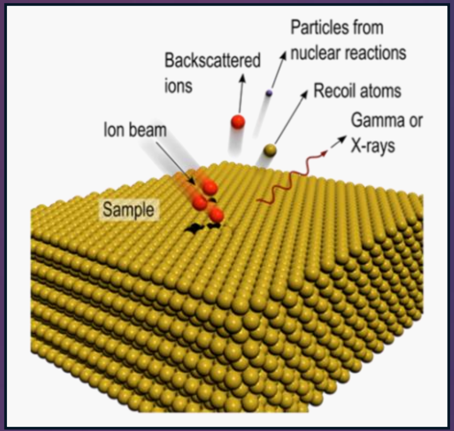
An old soviet-built tugboat connected to a movable electron accelerator for crop sterilisation. Demonstrated efficient NOx removal (no Sulphur allowed in port).

# Ion Beam Analysis

Analytical techniques exploiting the interactions of MeV protons or heavier ions with matter to determine the elemental composition and structure of the surface regions of solids (to depths of about 100 $\mu$m), from spectra of resulting X-rays, gamma-rays or particles.

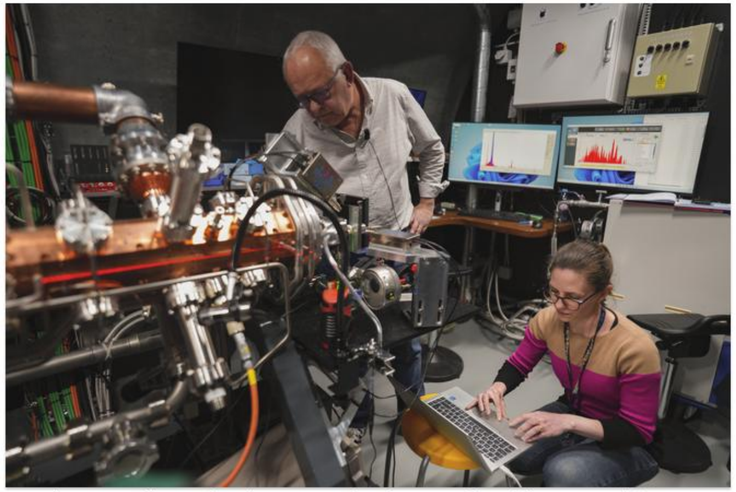
Ritratto Trivulzio by Antonello da Messina, 1476 – analysis at INFN-LABEC (Florence)

- Elastic or Rutherford backscattering (EBS or RBS), with a particle detector at a backscattering angle;
- Particle-induced X-ray emission (PIXE), with an X-ray detector;
- Particle-induced gamma-ray emission (PIGE), with a gamma detector;
- Elastic recoil detection analysis (ERDA) with a particle detector at a forward recoil/scattering angle.




Portable PIXE system based on an RFQ linac built by CERN and LABEC

# The RFQ proton accelerator for cultural heritage – open to visitors at CERN



## Science Gateway's mini accelerator is now taking data

**The mini proton accelerator ELISA, situated in CERN's Science Gateway exhibition centre, has started analysing archaeological samples**

22 NOVEMBER, 2024 | By Naomi Dinmore

Serge Mathot, CERN applied physicist, and Tessa Charles, accelerator physicist from ANSTO, performing the first experiment with the mini accelerator ELISA which is now being used for real heritage research in Science Gateway's "Discover CERN" exhibition. (Image: CERN)

A particle accelerator on display in a museum exhibition is rare. But a functioning particle accelerator conducting real scientific research in a museum exhibition? That's unprecedented. After years of development, the proton accelerator ELISA (Experimental Linac for Surface Analysis) is now being used for archaeological research at Science Gateway, CERN's education and outreach centre. This marks the first time a proton accelerator of this kind has been used for research as a part of a museum exhibition.

CERN Bulletin


A small proton accelerator (2 MeV energy, 1 m length) is now permanently installed in the new public Science Exhibition at CERN, the Science Gateway. Accessible to visitors, will perform cultural heritage analysis.

iFAST

# Challenges: the miniature accelerator

To increase the diffusion of particle accelerators, the main challenge for the accelerator designers is to conceive "**miniature accelerators**", providing the required beam parameters with minimum footprint, accessible cost, and low power consumption and environmental impact.

**New incremental and disruptive particle accelerator technologies**

| Category | Particle | Configuration | Energy/Footprint | Main limitations |
|---|---|---|---|---|
| **Incremental** technologies (RF-based) | protons | mini-RFQ | ~ 2 MeV/m$^2$ | RF power density, beam acceptance |
| | protons | mini-cyclotron | ~ 5 MeV/m$^2$ | Shielding, magnet weight |
| | electrons | High-frequency NC and SC linacs | ~ 20 MeV/m$^2$ | Breakdown rate |
| **Disruptive** technologies (laser-based) | p, ions | laser accelerator | ~ 10 MeV/m$^2$ | Energy dispersion, beam emittance, efficiency |
| | electrons | dielectric laser (DLA), plasma | ~ GeV/m$^2$ | Beam optics, thermal loading, radiation damage, efficiency |


INNOVATION / SCIENCE

**First ever prototype particle accelerator made using additive manufacturing technology**

6. December, 2022
Author: Anda Asere

Publicity photo

For the first time in history, a prototype particle accelerator component for medical and industrial applications has been 3D printed from a single piece of pure copper using the additive manufacturing technology. It was

Many directions to explore and exciting R&D:

- Additive manufacturing (integrated systems)
- AI and machine learning for automatised operation
- Use of lasers as power sources

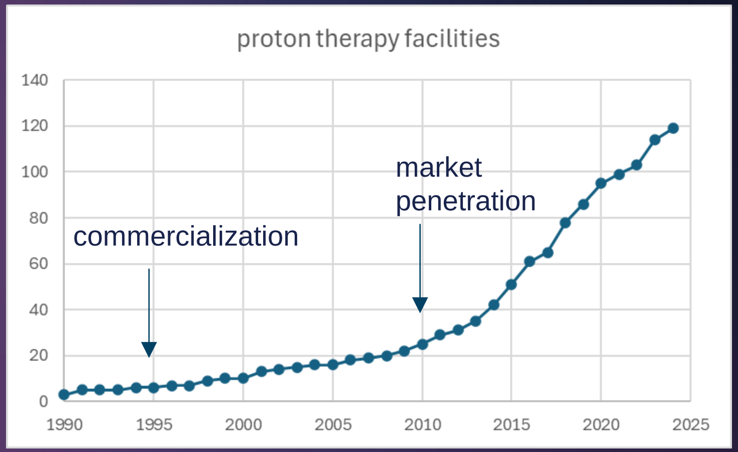
# Challenges: the long time constant from science to market

Accelerators are expensive objects; their progress requires long development times and considerable investments.
Technologies developed for basic science with public funding need to transit to commercial companies.

| | Commercialization Milestones | | | |
|---|---|---|---|---|
| | First proposed | First built | Commercial | Development time |
| Ion Implantaters | 1949 | 1965 | 1971 | 22 years |
| Medical electron linacs | 1952 | 1953 | 1965 | 13 years |
| Medical linacs - SW | 1965 | 1973 | 1980 | 15 years |
| Proton Beam Therapy | 1947 | 1989 | 1995 | 38 years |
| Carbon Beam Therapy | 1957 | 1994 | 2024 | 67 years |
| Electron Beam Welders | 1947 | 1954 | 1963 | 26 years |
| Cyclotron radioisotopes | 1930's | 1950 | 1965 | 35 years |

Table credit: update and extension from R.W. Hamm, EuCARD2 workshop, 2016

Need of technology transfer schemes, public/private partnerships, etc.



# To conclude…

**Particle accelerators can become crucial actors of the 4th industrial revolution** allowing industry and medicine to exploit technologies based on accessing to and interacting with the atomic and subatomic level.

*The 4 industrial revolutions*
*(4th still ongoing!)*

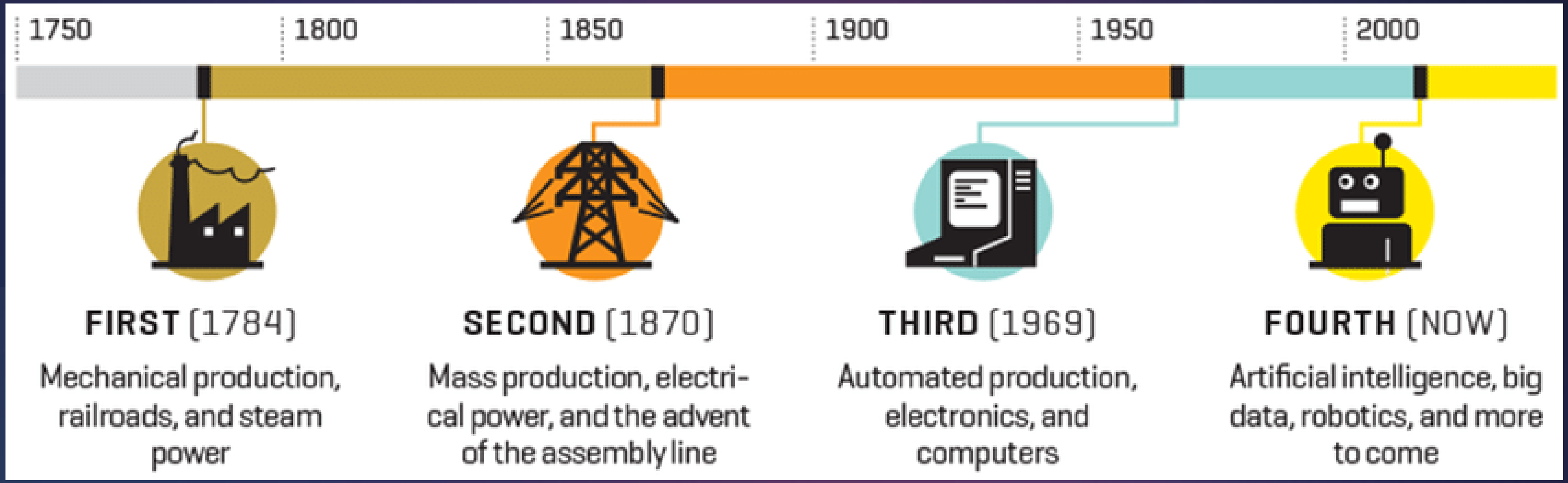



*Image credit: B. Horvath, S. Mundi, 2018*

Mechanics, Chemistry

Electricity

Electronics

*the 4th Industrial Revolution will be driven by the convergence of digital, biological, and physical innovations.*

*Accelerators are instruments that may open new dimensions in industrial, medical, and chemical processes and technologies*

# Thank you for your attention