Accelerators for health and industry

Maurizio Vretenar, CERN

3rd Workshop on Research and Innovation in Poland

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Instutute of Nuclear Physics Polish Academy of Sciences



ATS
Accelerators and Technology Sector

Particle accelerators for society

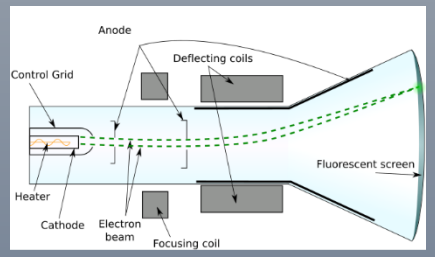
Nearly 45’000 particle accelerators in operation around the world:

- 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 simple electron accelerators.



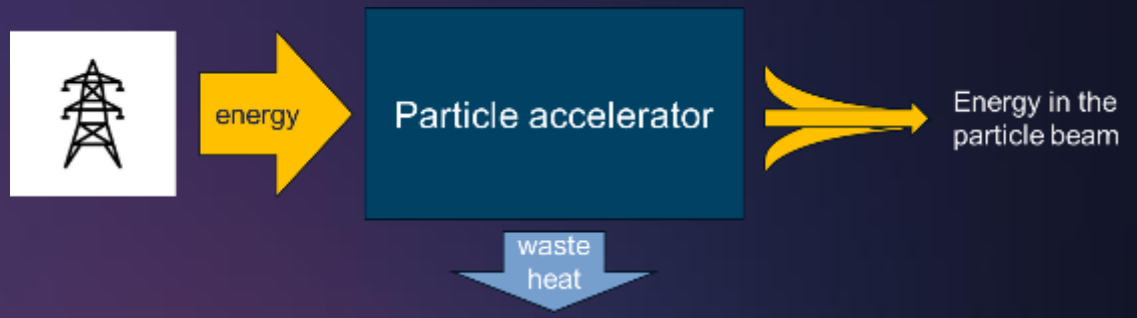
Image credit: Wikimedia commons



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?

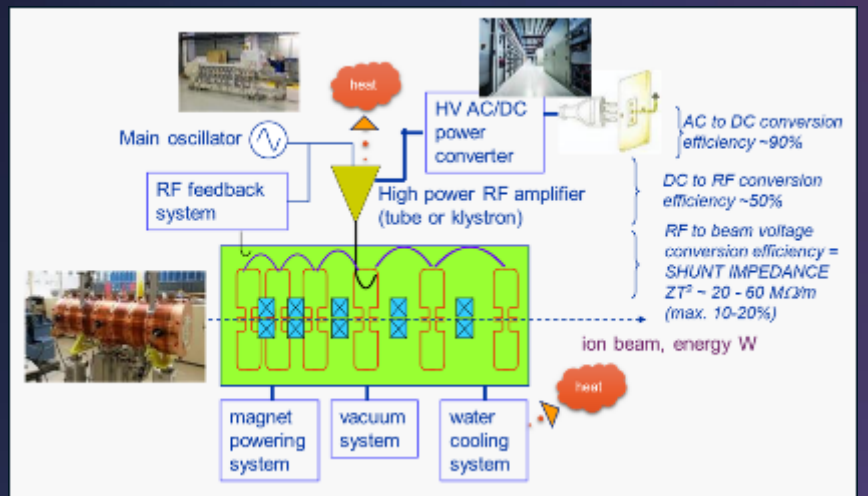
An accelerator is an instrument to concentrate energy at subatomic scale, enabling us to probe and manipulate matter at the level of atoms and subatomic particles



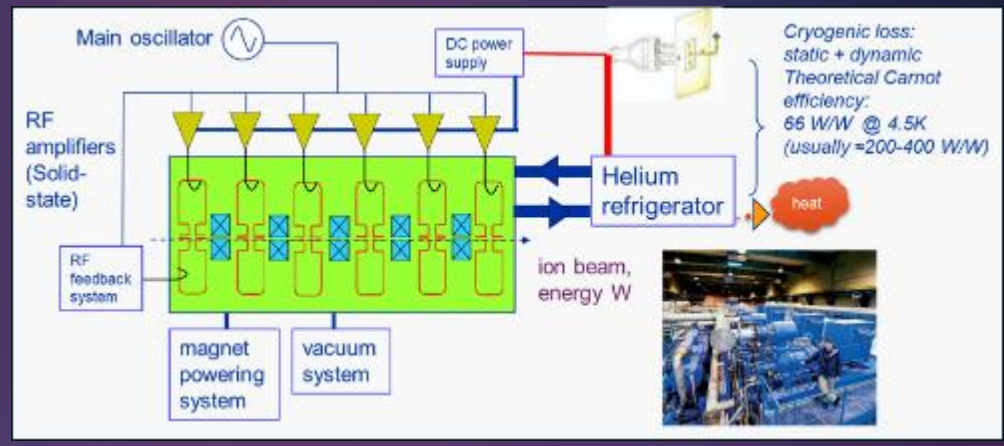
What limits the process and its applications is the energy efficiency

The process of concentrating energy into a particle beam (low entropy state!) requires to waste a large amount of energy. In the accelerator, 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.

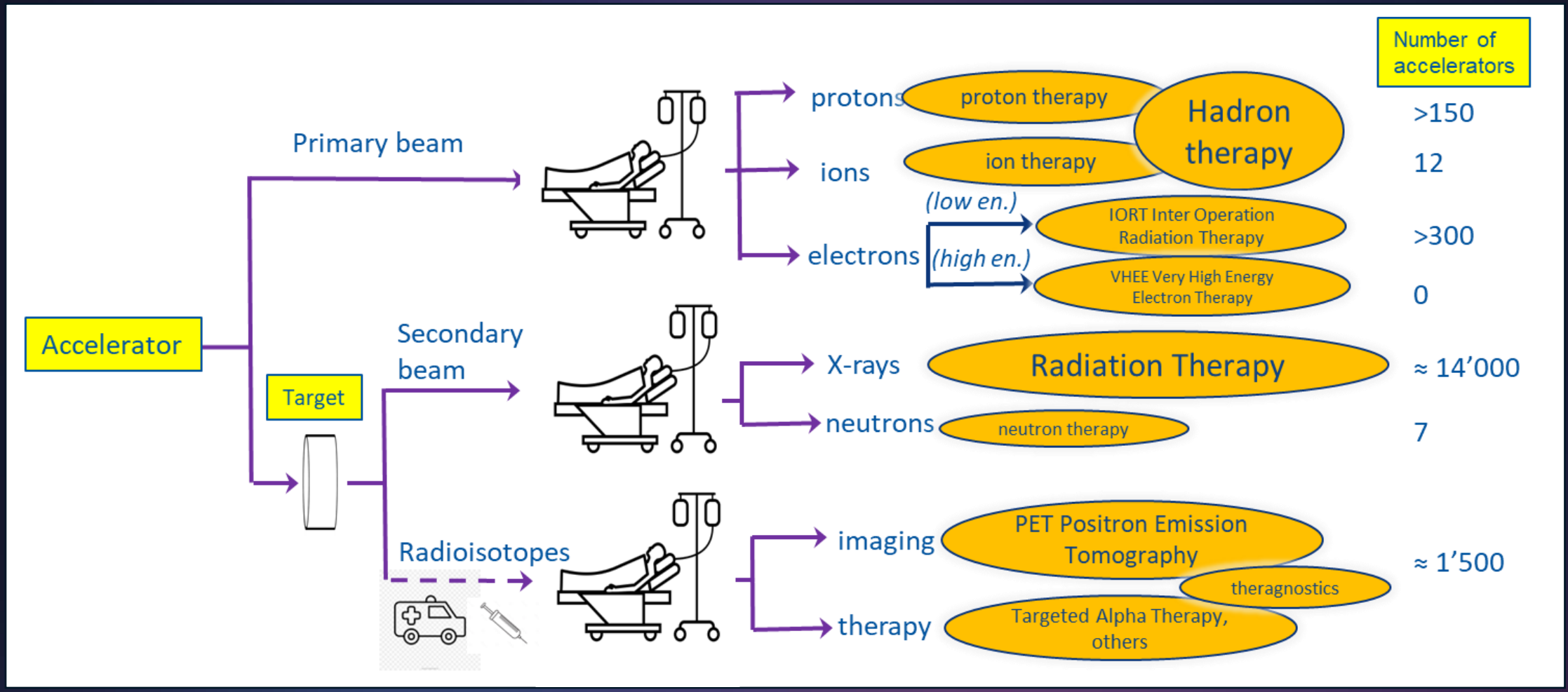
Normal conducting accelerator



Superconducting accelerator



Accelerators for health – an overview



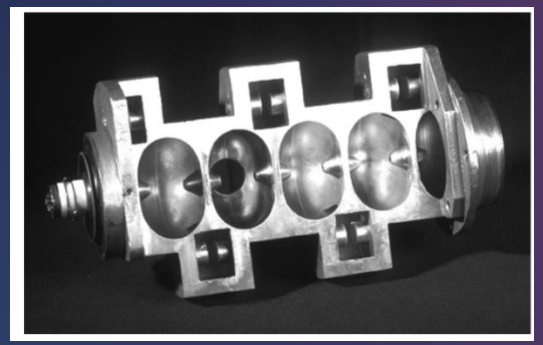
X-ray radiotherapy linac, the pillar of cancer therapy

~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.





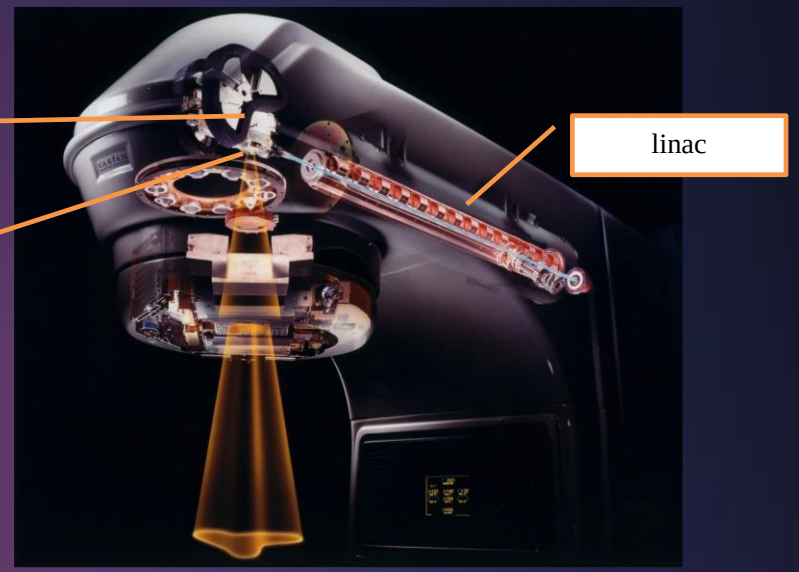


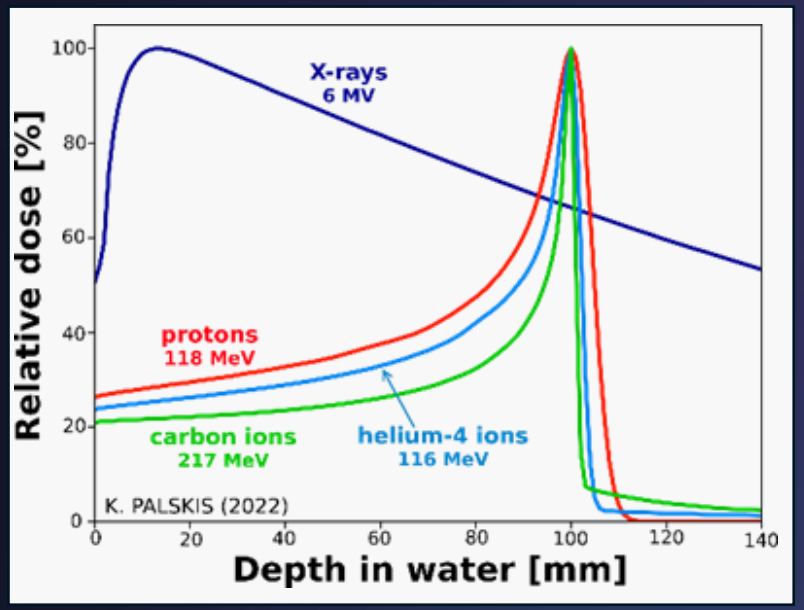
Image credit: Varian Medical Systems, Inc.

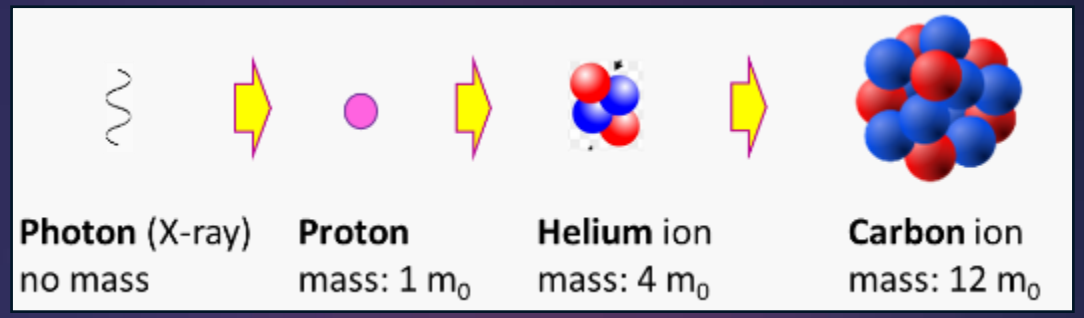
Nearly 17,000 in operation worldwide
(https://dirac.iaea.org/)

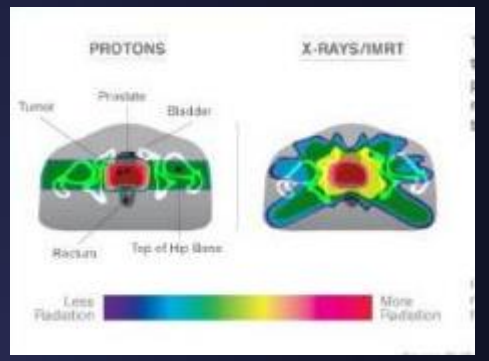
Side-coupled standing-wave linac structure, developed in 1967 for the Los Alamos Meson Facility. Thanks to its efficiency and stability equips most of present radiotherapy linacs

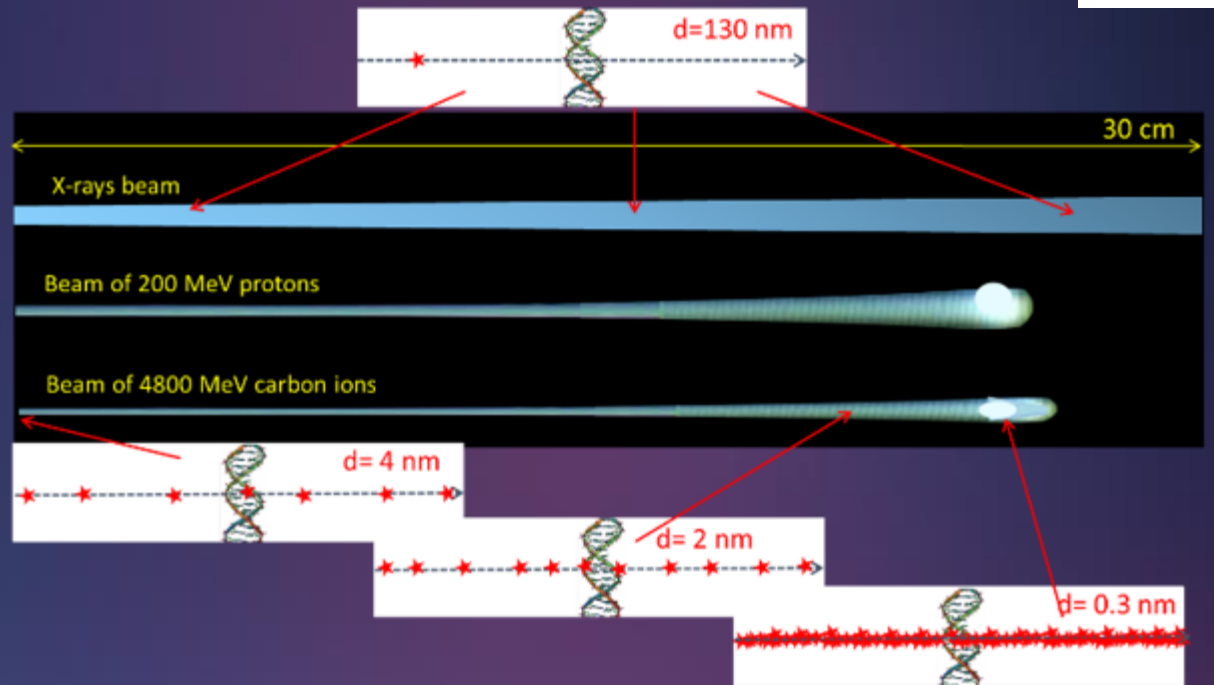
Good example of technology transfer from scientific to industrial accelerators

Treating cancer with beams: protons, carbon,…









- X-ray energy deposition decreases with depth.
- Protons and ions present a peak (Bragg) at a depth increasing with energy, **minimising the dose to the organs close to the tumour**.
- Linear Energy Transfer proportional to Z^2

Carbon ions cause double strand DNA breakings that are not repairable → are effective against “radioresistant” tumours.

Accelerators for particle therapy

For a given magnetic field, the accelerator radius is proportional to particle momentum at top energy.

Higher mass → higher energy loss → higher entrance energy →larger accelerator





Linac, X-rays
~50 m²
~few M€

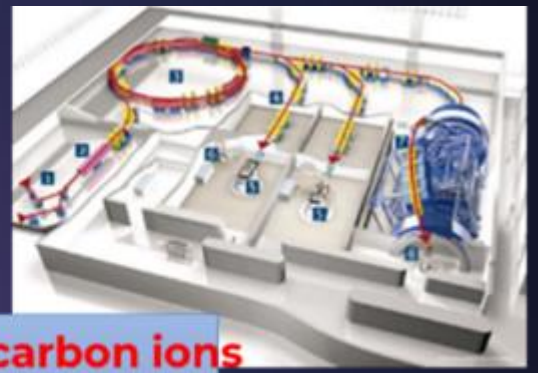


courtesy IBA



Cyclotron, protons
~500 m²
~few 10 M€





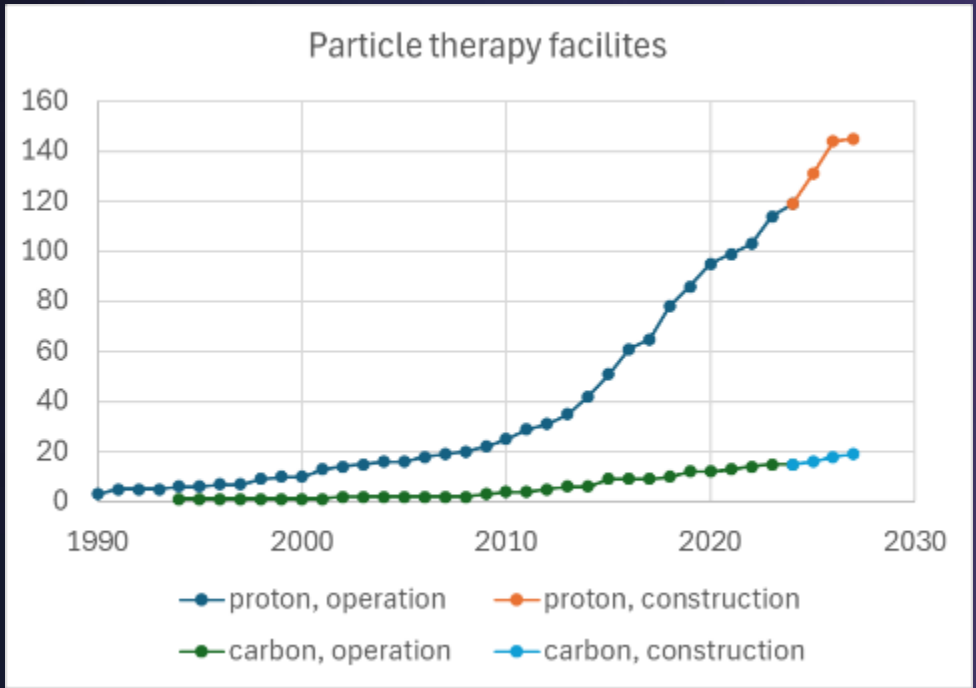
Synchrotron, carbon ions
~5,000 m²
>200 M€

Commercially available → Specially designed and built

Proton therapy: cyclotrons or synchrotrons available from vendors.

Carbon ion therapy: large facilities (4 available in Europe), only now starting to become commercial (mainly synchrotrons, one cyclotron in construction).

The rise of particle therapy



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

- 8 new proton and <1 new carbon facilities per year. Steady growth, but not too fast.
- Particles are a precision “scalpel”, but still expensive and requiring utmost accuracy in dose deposition.
- 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.

Particle therapy of cancer is still at its infancy. Many more data are needed, at the level of pre-clinical and clinical research.

New accelerators for particle therapy

How to reduce size and cost of the accelerator?

Accelerators for helium therapy

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

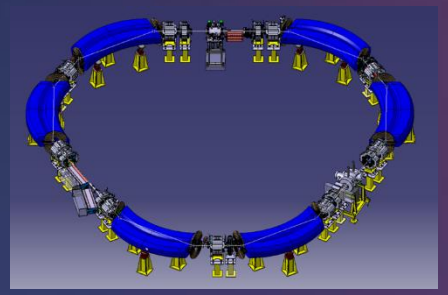


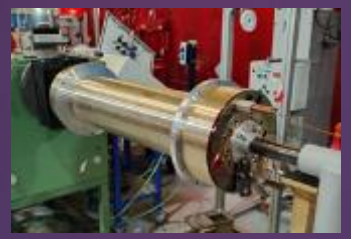
M. Vretenar. et al., (2023). Conceptual design of a compact synchrotron-based facility for cancer therapy and biomedical research with helium and proton beams, IPAC23 Conference, https://cds.cern.ch/record/2887018/files/document.pdf

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

Superconducting synchrotron for carbon therapy

Using High temperature superconducting magnets of new design, the triangular-shaped synchrotron developed for helium could accelerate carbon ion to treatment energy, providing a compact and low-consumption alternative to large normal-conducting synchrotrons.





Design of a SC synchrotron for carbon ion therapy, using CCT or superferric HTS.

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.



C. Rossi. et al., (2024), The Deep Electron FLASH Therapy facility, LINAC24 Conf., https://inspirehep.net/files/4891477b8864c919f74b864dd0e9273e

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

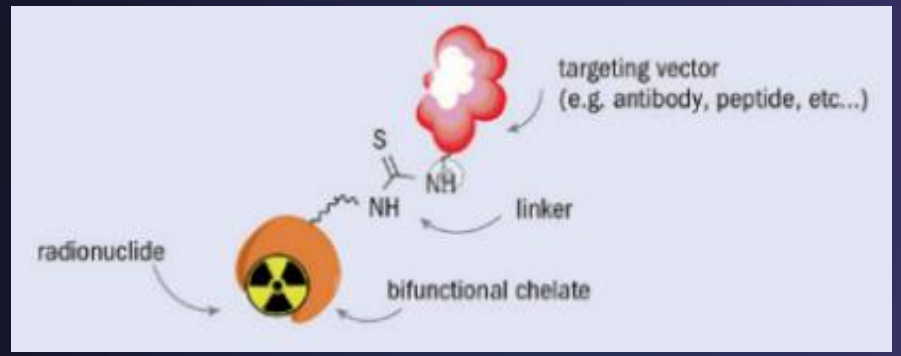


Image credit: CERN Courier

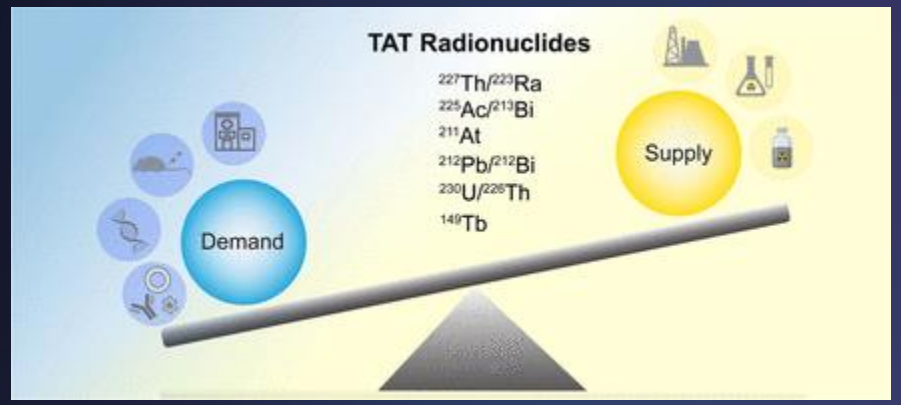


Image credit: V. Ratchenko, Journal of Nuclear Medicine November 2021, 62 (11) 1495-1503

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).

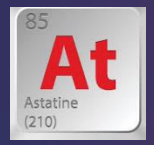
Expectations for a strong demand of compact accelerators for production of alpha emitters – close to hospital, to use isotopes with short-lifetime.

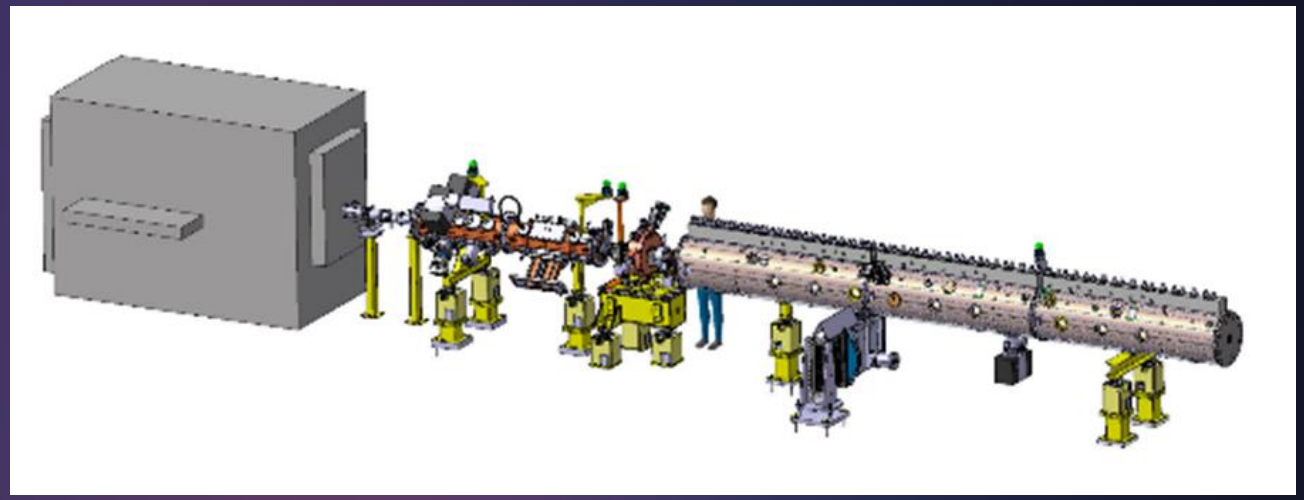
Linac for Astatine production

Astatine is the rarest element on earth
Only 30g present at any given time

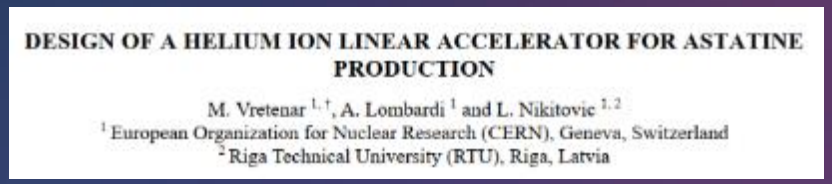
A short (12 m) linear accelerator of α-particles for production of isotopes, at energy (28.4 MeV) optimised for production of 211 Astatine (half-life 8.1 hrs).

Total length	11.5 m
RF frequency	352.2 MHz
Peak beam current	5 – 20 mA
Duty cycle	10%
Repetition frequency	50 Hz
Beam pulse length	2 ms
Average beam current	0.5 – 2 mA
Peak RF power (without beam)	1.1 MW
Maximum RF power (20 mA beam)	1.35 MW





- Initiative of the TERA-CARE Foundation (Prof. U. Amaldi) for a new nuclear medicine and particle therapy facility in Switzerland (CHeFS, Clinical helium Facility for Switzerland) adopting this linac design as first stage.
- Collaboration CERN-Uni. Bern on target design.
- Interest from other institutions (CNAO, Italian particle therapy centre).


DESIGN OF A HELIUM ION LINEAR ACCELERATOR FOR ASTATINE PRODUCTION

M. Vretenar [1,†], A. Lombardi [1] and L. Nikitovic [1,2]
[1] European Organization for Nuclear Research (CERN), Geneva, Switzerland
[2] Riga Technical University (RTU), Riga, Latvia


Tera Care

"CHeFS"
A CLINICAL HELIUM FACILITY FOR SWITZERLAND
A proposal

Ugo Amaldi, Elena Benedetto, Saverio Braccini and Frédérick Bordry
Tera-Care Foundation, Geneva

Accelerators for industrial processes and sterilisation

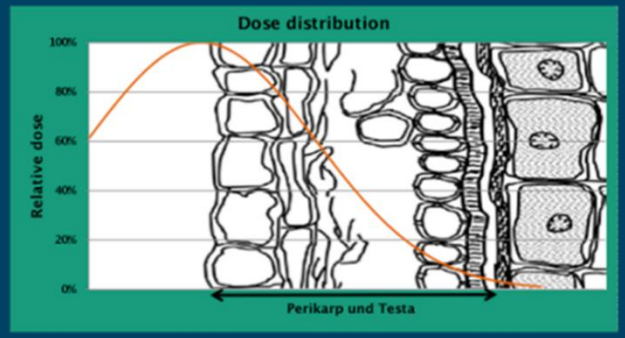
	Energy	Applications
Very low energy electrons	<350 keV	detection, welding, 3D-sintering, sterilisation, seed and grain treatment
Low-energy electrons	<10 MeV	polymer modification, sterilisation, treatment of flue-gas, wastewater, sewage



- 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 - 30% of food harvested 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 DNA.

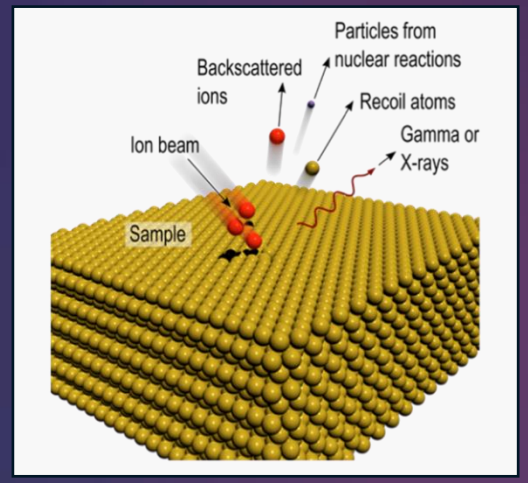


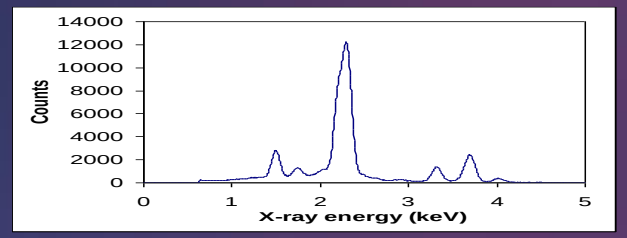
LIMITATION to sterilization: low social acceptance of “radiation” technologies

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 μm), from spectra of resulting X-rays, gamma-rays or particles.

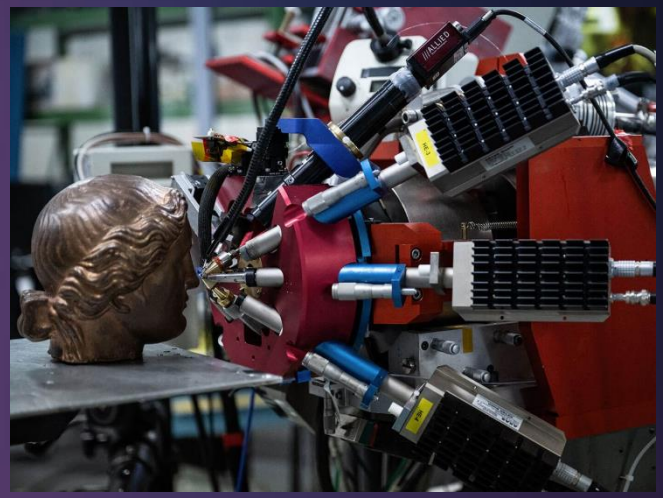
- Elastic or Rutherford backscattering (EBS or RBS), with a particle detector at a backscattering angle;
- Particle-induced X-ray emission (PIXE), with an X-ray detector;
- Particle-induced gamma-ray emission (PIGE), with a gamma detector;
- Elastic recoil detection analysis (ERDA) with a particle detector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







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

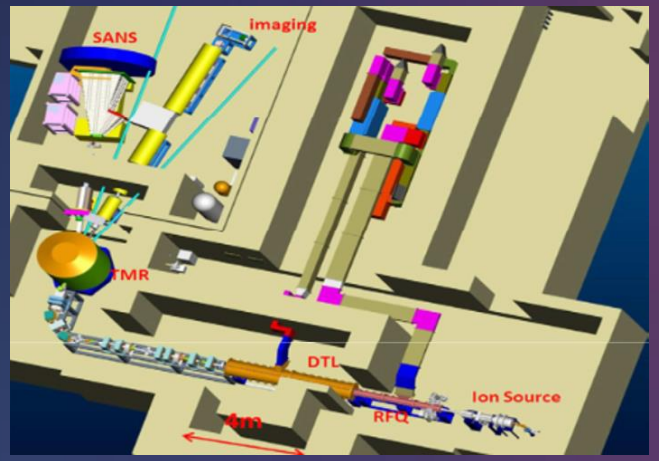


Analysis of an artifact at the AGLAE accelerator of the Louvre museum (Paris).

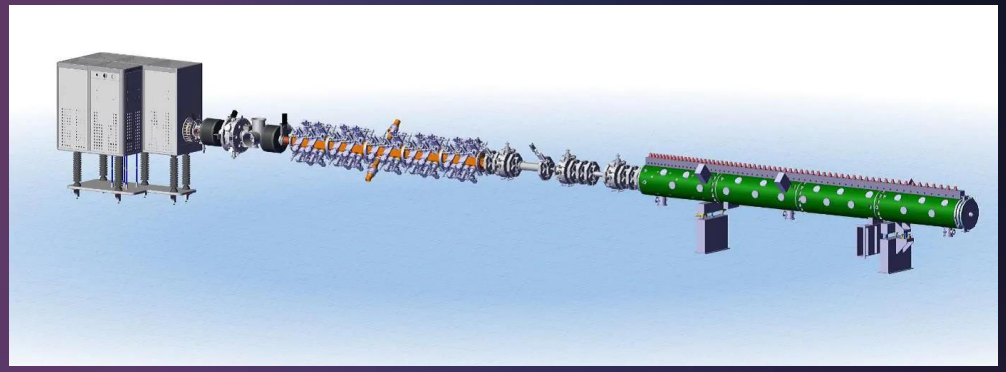
Neutron radiography and imaging

Complementary to X-ray radiography, **neutron radiography** (sensitive to light elements) has applications in many fields:
Materials: Small-Angle Neutron Scattering (SANS) to investigate fluids, polymers, and biological samples. Battery R&D.
Medical: Boron Neutron Capture Therapy (BNCT), radioisotopes.
Industrial: Neutron Radiography & 3D Imaging (corrosion in aerospace components, water transport in fuel cells, micro-cracks in metals), Stress Diffractometry, Quality control of metals, etc.

Compact Accelerator Neutron Sources (**CANS**): proton or deuteron beams, energy 2 – 30 MeV, high average current and high duty cycle operation. Use low energy reactions (Be or Li targets). Much lower yield than larger facilities (≈10^{-4}).



Compact Pulsed Hadron Source design at Tsingua Univ.



CANS design for ICONE (France)

Opportunities: new technologies

A new generation of compact, user-friendly accelerators is emerging, enabled by technologies now on the horizon:

- ❑ Precise **Additive Manufacturing** of metals and multi-materials: reduce production time and cost for sophisticated parts with improved cooling structure.
- ❑ New **High-Temperature Superconductors**, permitting higher magnetic fields with reduced power consumption.
- ❑ Extensive use of Machine Learning and **Artificial Intelligence**, simplifying operation with potential for changing the business model of commercial accelerators.
- ❑ New acceleration technologies based on **lasers and plasmas**: acceleration of low-intensity beams to very high energies.



AM-Radio Frequency Quadrupole prototype





REBCO (Rare-Earth Bismuth Copper Oxyde) tape and prototype magnet

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!)

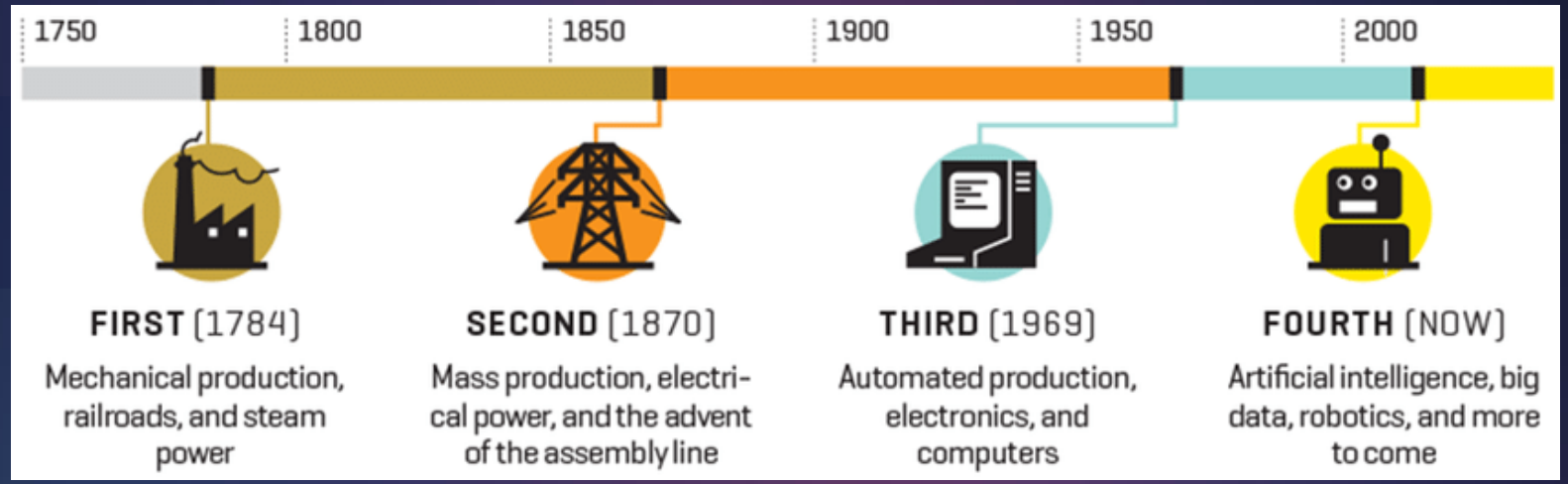


Image credit: B. Horvath, S. Mundi, 2018

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

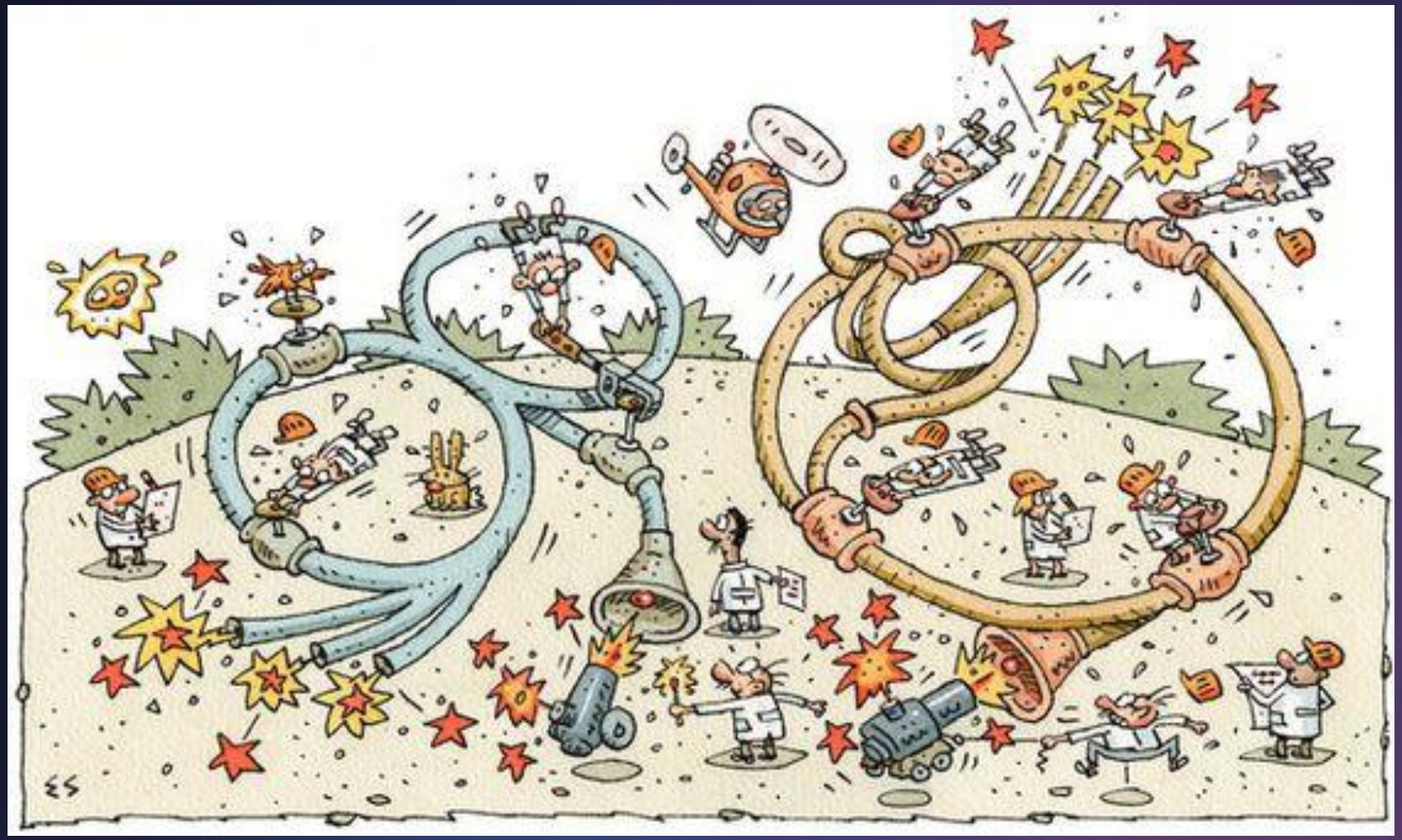
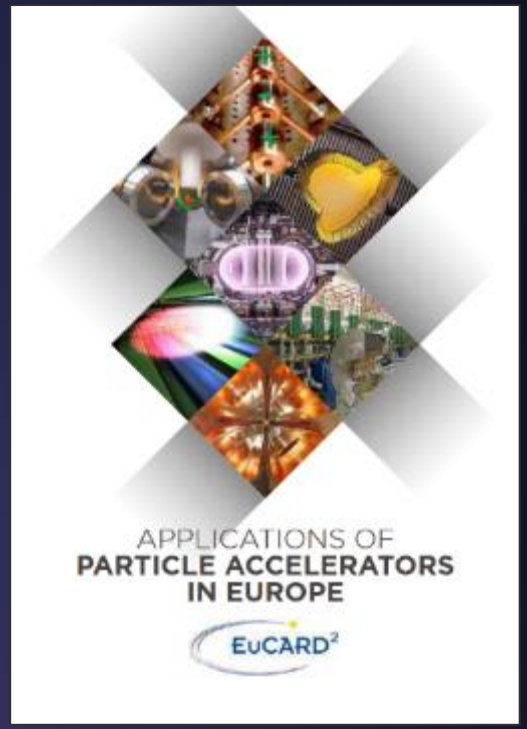


Image credit: Elwood Smith, NYT



Further reading:
Eucard2 report on Applications of Particle Accelerators in Europe (2017),
https://ifast-project.eu/sites/default/files/2021-09/EuCARD-Applications-of-Accelerators-2017.pdf